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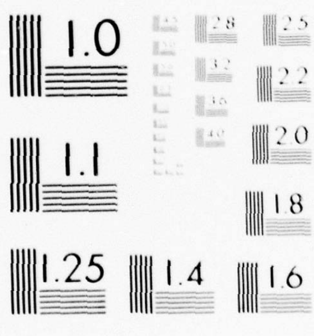

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A STUDY TO DEVELOP OPTIMIZATION ALGORITHMS FOR AIRCRAFT WING STRUCTURES

Gerald W. Abbott, Captain, USAF
Robert A. McNamara, Jr., Major, USAF

LSSR 23-79A

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Increasing cost and complexity of major weapon systems have resulted in many methods that constrain cost while assuring development of weapon systems that meet the military need. Among these methods the use of cost estimating relationships embodied in computerized mathematical modeling has come to the forefront. This research uses the Vehicle Design Evaluation Program (VDEP), a model which designs a least-weight aircraft. Since a least-weight aircraft may not be a least-cost aircraft, this research examined the feasibility of developing algorithms to relate least-cost to design using VDEP. Various graphic and statistical techniques failed to yield meaningful relationships. Additional analysis revealed apparent discrepancies in VDEP structural synthesis routines. Further research is recommended using more advanced design/cost models which incorporate revised structural synthesis routines. These models should first be validated for proper design/cost estimating properties. Then research should be conducted to identify cost driving parameters and detailed variable relationships. In this way the attainment of minimum cost aircraft structures which meet mission needs will materialize.

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A STUDY TO DEVELOP OPTIMIZATION ALGORITHMS FOR AIRCRAFT WING STRUCTURES

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Logistics Management

By

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June 1979

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This thesis, written by

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and

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has been accepted by the undersigned on behalf of the faculty of the School of Systems and Logistics in partial fulfillment of the requirements for the degree of

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CHAPTER I

INTRODUCTION

> Our policy is to reduce the price, extend the operations, and improve the article. You will notice that the reduction of price comes first. We have never considered costs as fixed. Therefore we first reduce the price to the point where we believe more sales result. Then we go ahead and try to make the prices. We do not bother about the costs. The new price forces the costs down. The more usual way is to take the costs and then determine the price, and although that method may be scientific in the narrow sense; it is not scientific in the broad sense, because what earthly use is it to know the cost if it tells you that you cannot manufacture at a price at which the article can be sold? But more to the point is the fact that, although one may calculate what a cost is, and of course all of our costs are carefully calculated, no one knows what a cost ought to be [7:263].

The Department of Defense (DoD) formalized two procedures for acquisition of major defense systems through DoD Directive 5000.1. This directive established cost as a co-equal to design specifications and system performance. The directive required that cost parameters consider the cost of acquisition and ownership, and that distinct cost elements, such as unit production cost, be translated into "design to" requirements. Cost parameters will be evaluated with the same strictness as technical requirements (30:4).

The design to cost (DTC) process was formalized and adopted by DoD in order to use unit cost goals as thresholds for managers and as design parameters for engineers. DoD

Directive 5000.28 established the framework for DTC and encompassed the requirements of DoD Directive 5000.1 for major defense systems (31:2). To date the objectives of DTC have not been met and cost growth continues to be a problem in major weapon system acquisition (27). The establishment of improved techniques for estimating costs and realizing the optimum trade between cost and performance will aid in realizing DTC.

Background

This research area has been identified by the U.S. Air Force Flight Dynamics Laboratory (AFFDL) at Wright-Patterson AFB, Ohio. The AFFDL Structures Division is responsible for obtaining structural cost estimating data to be used in the development of cost estimates for aircraft design. Cost data are obtained from the computer program, Vehicle Design Evaluation Program (VDEP), which designs an aircraft structure according to a constraint of minimum weight (21:1). VDEP provides a vehicle synthesis capability that includes vehicle sizing, structural analysis, and cost evaluation (27).

Cost evaluation in VDEP is accomplished through optimization routines that attempt to design a minimum weight airframe. VDEP has no automated search or optimization routines that would attempt to design airframes at minimum cost. The cost of a particular aircraft design can

be estimated by using the program; however, whether a minimum cost design has been obtained is not known (27).

Design to Cost Concept

In June of 1973 the first step toward Design to Cost (DTC) implementation was taken. In that year Deputy Secretary of Defense William P. Clements, Jr. issued a memorandum to the Secretaries of the Military departments and the Defense Systems Acquisition Review Council to establish DTC goals for major defense system programs (2:65). Design to Cost is:

> . . . a management concept wherein rigorous cost goals are established during development and the control of systems costs (acquisition, operating and support) to these goals is achieved by practical tradeoffs between operational capability, performance, cost and schedule; cost, as a key design parameter, is addressed on a continuing basis and as an inherent part of the development and production [2:65].

The essence of DTC is that the designer must put cost considerations on an equal footing with performance considerations. This concept gained impetus when DoD Directive 5000.28, entitled "Design to Cost," was published in May 1975. The reasons for initiating the DTC program were many: excessive cost overruns, decreasing percentage of the national budget for military appropriations, increased cost of military manpower, and inflationary trends (15). DTC established unit cost goals as thresholds for managers and design parameters for the engineers. Funds were not to

be spent beyond the point where costs rose rapidly for small incremental increases in performance (29:4).

The response to the DTC methodology was encouraging. "Designers responded to the O & S cost challenge and became adept at designing out cost-increasing components or maintenance processes [5:6]." However, a recent General Accounting Office (GAO) report in 1978 indicates that the major acquisitions at the end of September 1977 were estimated to have a completion cost 72 percent over initial estimates (15).

The Total System

Largely as a result of failures to accurately predict the total or life cycle cost (LCC) of major weapon systems, there has been increased interest in computer models that demonstrate ability to predict such costs. Figure 1 illustrates graphically the LCC problem.

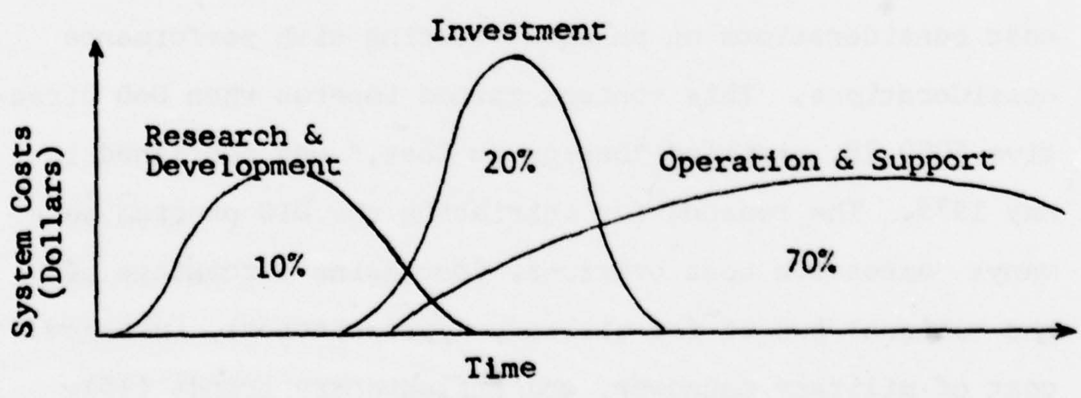


Figure 1. Life Cycle Cost of Major Defense System (12)

The majority of the cost of a major weapon system does not occur until that system is actually in operation. Initial system cost is only ten percent of the long-run or LCC of the system.

As depicted in Figure 2, the area of research is within the preliminary design portion of the Research and Development Phase of LCC. The airframe portion of preliminary design has been singled out for study because of the potential savings available through changes in this area.

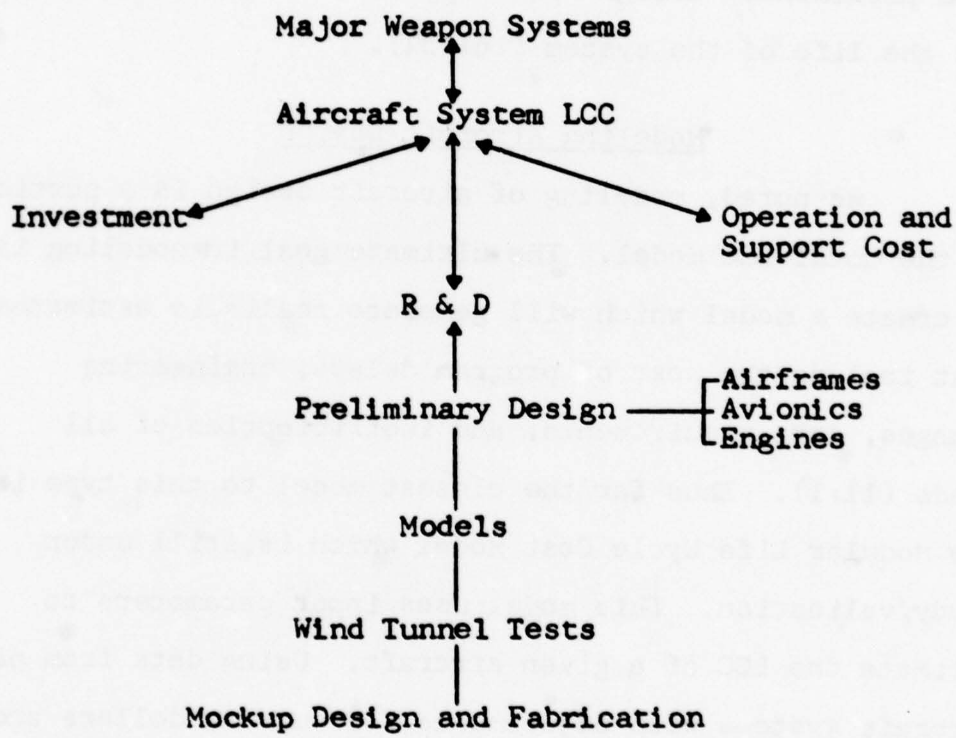


Figure 2. Total System Cost Diagram

With cost as a significant design parameter equal to performance, real dollar results can be developed early in the life cycle of the system (16:45). The heart of this concept of LCC is the unit cost of the system under consideration; the critical cost is the unit production cost (26:12-13). Presently, the airframe represents one third to one half of the total production costs of an aircraft (33:189). However, 80 percent of LCC is fixed before the start of full scale development; therefore, savings derived from preliminary design will impact upon the costs throughout the life of the system (16:451).

Modeling Aircraft Design

As noted, modeling of aircraft design is a portion of the total LCC model. The ultimate goal in modeling is to create a model which will generate realistic estimates that include the cost of program delays, engineering changes, data requirements, and inefficiencies of all kinds (11:1). Thus far the closest model to this type is the Modular Life Cycle Cost Model which is still under study/validation. This model uses input parameters to estimate the LCC of a given aircraft. Using data from past aircraft systems with adjustments for current dollars and other factors, this model has been a good predictor to within 30 percent of actual costs (27). The Vehicle Design and Evaluation Program (VDEP) model which is to be used in

data evaluation for this research is based upon design parameters. More specifically, it optimizes design based upon minimal weight for the airframe structure. Its intended use is to assist the airframe designer (27). The intention of this research was to aid in the development of algorithms for use in the VDEP program.

Most major aircraft companies use models in comparing estimates for aircraft costs.

> In system studies where a number of alternative ways of achieving a specific objective are to be evaluated, a cost model provides consistent, comparable estimates and does so quickly and cheaply [11:v].

Automated structural design models will not, under the present stage of development, automatically choose the optimum structural design concept. Rather, they will find the optimum configuration dimensions for a given structural concept subject to a given set of design variables and configuration (10:14-1). Thus, the big task in model formulation is to define the cost relationships for two or more variables within a given set of past data. In essence, designers and producers are looking for estimators that will provide consistently accurate estimates, are logically related to cost, and can be determined prior to final design and development (11:1). Based upon these results, extrapolations are made into the future.

Weight/Cost Tradeoff

Through investigation of past cost relationships three basic variables have been found to be most useful in prediction of aircraft cost: aircraft gross weight, speed, and engine thrust (14:3). Of these, weight is the variable most often used for prediction (22). With the exception of electronic gear, weight appears to explain more variations in cost than any other physical characteristic. Airframe structure generally represents 60 percent of take-off weight empty. This figure may increase to as much as 75 percent with large aircraft (3:3). Of even more concern is the ratio of structural weight to payload. A small increase in the weight of a structure can cause large reductions in payload and range (33:2).

From the point of view of the designer, the primary function of the structure is to transmit forces through space. His objective is to do this with the minimum possible weight and at minimum cost (25:8). However, there is a point at which additional savings in weight is uneconomical. It is up to the designer to apply cost effectiveness evaluation to detailed design:

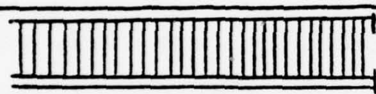
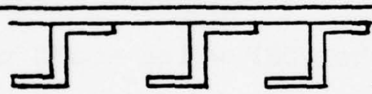
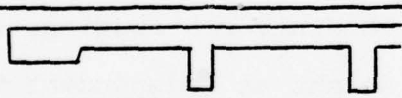
> . . . once we show the designer the LCC impact of his initial design approach, he gets the cost message and thereafter wants to see the LCC impact of each alternative approach. In this simple manner cost is becoming a major design parameter [16:45A].

The type of construction and type of material have a great effect upon the total resultant cost (23:49). Figure 3 demonstrates that point.

CANDIDATE STRUCTURAL/MATERIAL DESIGN EVALUATION:

- Cost: Material, Fabrication
- Weight: Structural Efficiency

Wing Structure Compression Panels

		Material		
Concept No.	Concept	Steel	T_i	AL
1		133 \$/FT^2 3.03LB/FT^2	----	10 \$/FT^2 4.57LB/FT^2
2		120 \$/FT^2 3.56LB/FT^2	170 \$/FT^2 2.67LB/FT^2	60 \$/FT^2 3.32LB/FT^2
3		91 \$/FT^2 3.6 LB/FT^2	130 \$/FT^2 2.76LB/FT^2	55 \$/FT^2 3.97LB/FT^2
4		----	190 \$/FT^2 2.97LB/FT^2	67 \$/FT^2 3.68LB/FT^2

(T_i = Titanium, AL = Aluminum)

Figure 3. Candidate Structural/Material Design Evaluation (34:192)

There are two steps in developing a cost/weight tradeoff. The first is the effect of weight saving on improved performance expressed in terms of dollars. The second step is the evaluation of weight and cost of candidate structural/material concepts which are equivalent in

load-carrying ability (34:189). It is important for the designer to know not only the optimum material for a particular design but also the weight effect of that material (29:9).

In our research the VDEP model was used in various design configurations with aluminum as the basic material. Aluminum withstands high structural impact loads (25:222). In addition, it is the primary airframe component of supersonic aircraft up to about mach 2.5 (1:24).

Problem Statement

A feasibility study, completed in June 1977, was designed to determine whether a series of design algorithms could be developed for use with the VDEP which would perform an "optimum tradeoff between minimum cost and minimum weight [6:1]." The research used wing cost as the dependent variable and regressed it with wing loading, rib spacing, structure types, skin thickness, and weight as independent variables (6:10). The data base for the analysis was the DC-10 wing.

While the research did not define precise algorithmic equations, the feasibility of such algorithms was shown (6:27). Multiple linear regression analysis showed that there was a relationship between the independent variables and cost. The most significant variables were weight, rib spacing, and structure type (integral blade); however,

when weight was deleted, the key design parameter became skin thickness. This suggested that skin thickness (T-bar) and rib spacing should be added to the list of key cost drivers.

> It is imperative to understand that a given T-bar and rib spacing are two primary factors which determine weight. Hence, the relationship between T-bar and rib spacing is an essential element in the development of a successful cost optimization algorithm [6:28-29].

It was concluded that the minimum cost occurred when the T-bar was in the range of 0.25 to 0.50 inches (6:29). The results of the research showed that additional analysis was necessary to develop a better indicator of cost as a function of the independent variables when T-bar values are in the range of 0.25 to 0.50 inches.

Scope

This thesis was conducted under the sponsorship of the U.S. Air Force Flight Dynamics Laboratory, Structures Division, at Wright-Patterson AFB, Ohio. The work is relevant to an aircraft structure design algorithm which would perform an optimum arrangement between minimum cost and minimum weight. The research was intended to increase the knowledge base concerning the use of VDEP for cost determination. Utilizing VDEP to analyze all structural variable combinations (over 360,000) would cost over 4.1 million dollars in computer time. This emphasizes the importance of developing an optimization algorithm rather than enumerating all of the variable combinations (24).

Research Objectives

The objectives of this thesis effort were to:

1. Identify more precisely the locations of the cost fluctuations in the range 0.25 to 0.50 inches T-bar (within the parameters of the independent variables).

2. Clarify the relationship between cost and the design parameters of wing loading, stringer spacing, rib spacing, structure types, skin thickness (T-bar), and weight to develop algorithms for an optimum cost aircraft structure.

Research Questions

1. What is the relationship between T-bar and cost in the range 0.25 to 0.50 inches?

2. What relationships exist, in the range 0.25 to 0.50 inches T-bar, between cost (dependent variable) and wing loading, rib spacing, stringer spacing, structure types, and weight (independent variables)?

CHAPTER II

METHODOLOGY

Overview of the Vehicle Design Evaluation Program Model

To understand how this research effort was conducted, it is essential that a general knowledge of the VDEP model be established. The major components of VDEP are shown below:

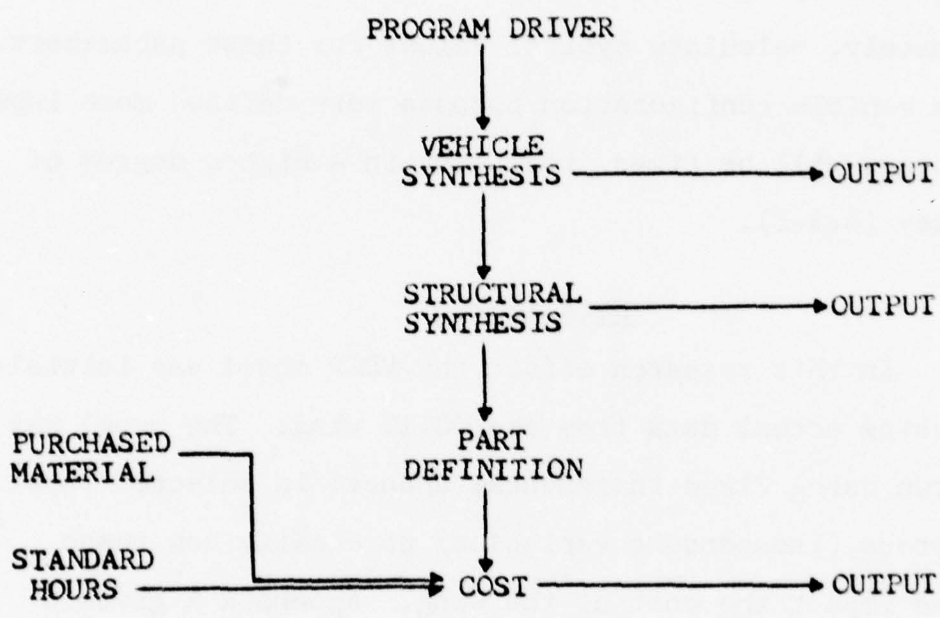


Figure 4. Major Components of VDEP

VDEP provides a "unique way of predicting the weight and physical design of each detail part of a vehicle structure at a time when only configuration drawings are

available [4:1-1]." The program has the ability to generate much of its own required data as a result of coupling several levels of synthesis routines together. As an example, the output of the vehicle synthesis routine is used as input by the structural synthesis routines, whose output in turn is used as input by the parts definition routines (4:3-2).

Another capability of the VDEP is the self-generation of optional input. The optional portion of input is comprised of a series of parameters not always known during initial design. The program will use values input or, alternately, calculate typical values for these parameters. As the vehicle configuration becomes more defined more input parameters will be fixed, resulting in a higher degree of accuracy (4:3-2).

Data Source

In this research effort the VDEP model was initialized using actual data from the DC-10 wing. The model was then run using fixed incremental changes in selected input parameters (independent variables) to examine how these changes impact the cost of the wing. Appendix A gives a more thorough discussion of the various components of VDEP and the input/output from its various routines. It is important to note that VDEP provides a distinct way of analyzing the sensitivity of cost to changes in input parameters.

The VDEP software package was used in conjunction with the CDC 6600 computer system located at the Aeronautical Systems Division (ASD), Wright-Patterson AFB, Ohio. All computer runs used the DC-10 data base. This data base consists of approximately one hundred punched cards with values for such factors as wing loading, cruising velocity, details of wing construction, production rates, dollar base year, and number in the production run. These values were used by Major Ronald L. Evans and Captain Bruce P. Christensen in their initial attempt to develop an algorithm to change the least weight output from VDEP into a least cost output.

As noted previously, the VDEP gives the least weight structure for the parameters specified, not necessarily the least cost structure. Since this research was a follow-on study to develop a least cost algorithm, the same data base (DC-10) was used. Selection of the DC-10 for the Advanced Tanker-Cargo Aircraft further yields applicability to this aircraft as a data source.

Variables

Variables selected for analysis were the same as those used in the previous research effort by Evans and Christensen, e.g. wing stringer types (shown in Figure 5), T-bar (T), weight (W), rib spacing (R), and wing loading (U). In addition to these independent variables, personnel

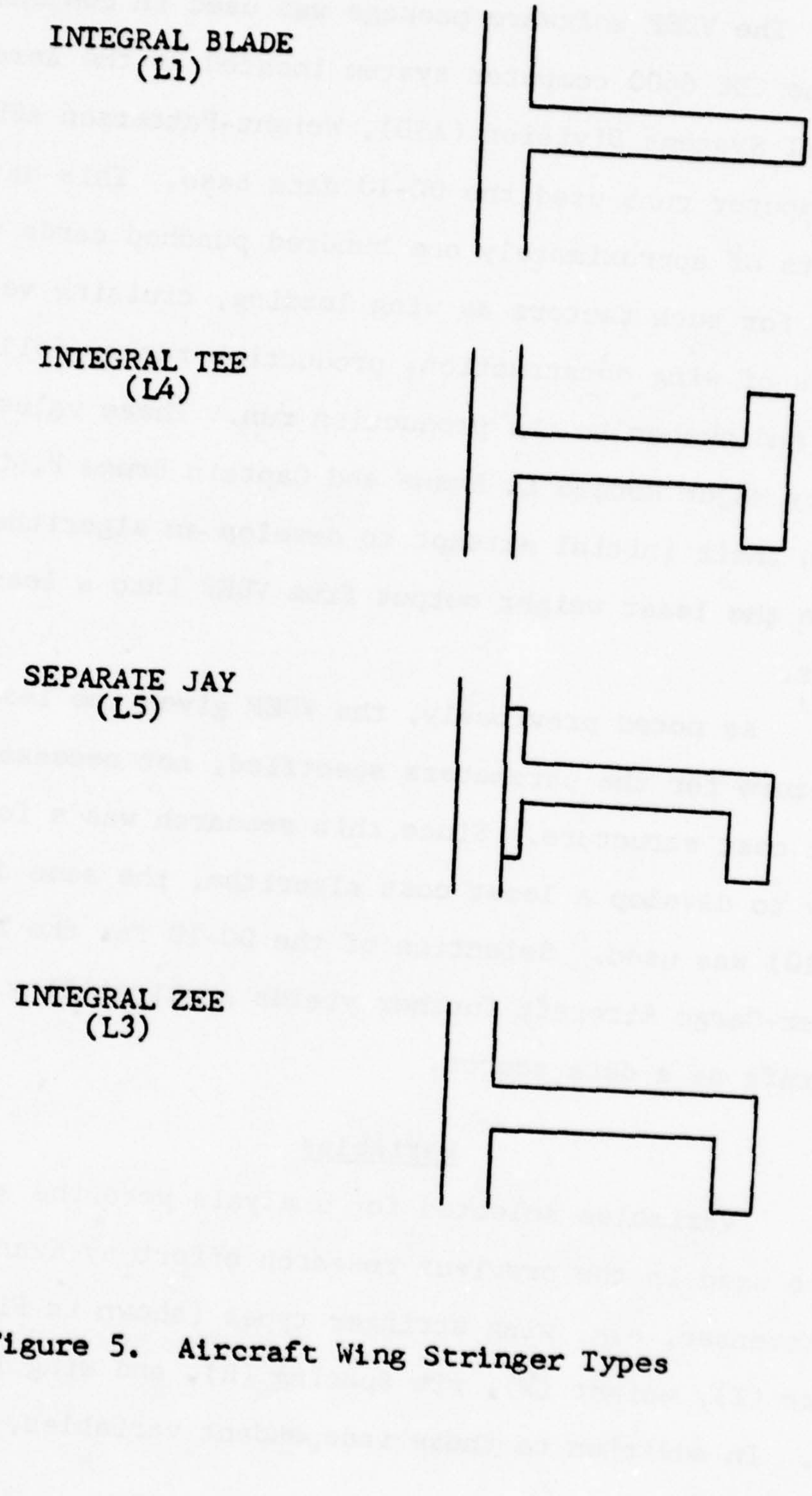


Figure 5. Aircraft Wing Stringer Types

of the AFFDL Structures Division requested that stringer spacing be included as an additional independent variable. The dependent variable is total cost for the DC-10 wing. This cost includes costs associated with tooling, manufacturing, overhead, and material acquisition. Aluminum was used as the fabrication material (27).

A word of caution is in order concerning these variables. In many cases the variable has been operationally defined for use in the VDEP program. T-bar is defined as wing area spread over distance to give an average thickness of the aircraft skin (27). Appendix B gives definitions for variables to be used in VDEP. The pictorial representation of a wing is given in Appendix C.

Sampling

All data for the DC-10 represent the universe for analysis. From this universe the wing structural data have been singled out as the population. A series of random samples of cost were generated, using VDEP and combinations of the independent variables named above.

Figure 6 represents pictorially the 44 combinations of a 26-inch rib spacing with the 4 stringer types and 11 wing loads for each stringer type. While rib spacing and stringer type were held constant, the wing loading was changed eleven times giving eleven values for skin thickness, stringer spacing, total weight, and total cost

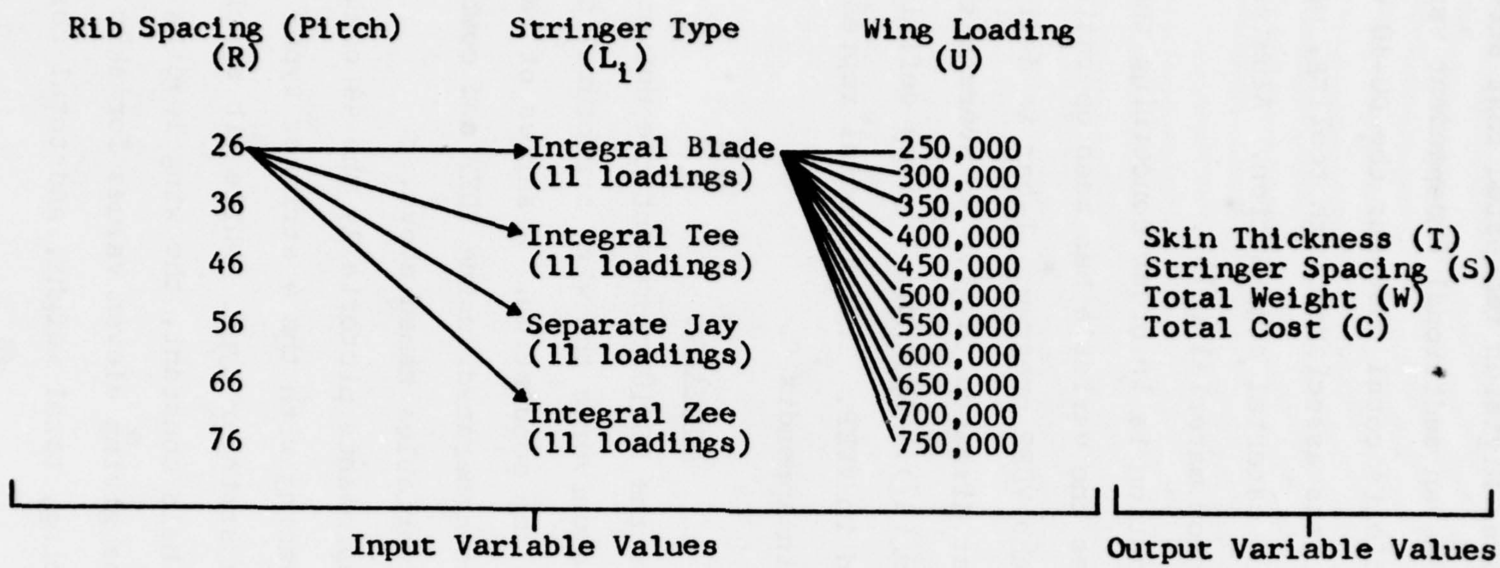


Figure 6. Input Variable Combination

respectively. Next, a different stringer type was chosen still keeping rib spacing at 26 inches. This change coupled with the eleven load factors generated another eleven values for each of the output variables. After the 26-inch rib spacing was systematically combined with all possible combinations of stringer type and wing loading, each of the output variables had 44 data values. The rib spacings of 26, 36, 46, 56, 66, and 76 inches resulted in 264 data points.

Whereas Major Evans and Captain Christensen selected wing loads to generate T-bar values between 0.25 and 3.0 inches, our wing loads generated T-bar in the 0.25 to 0.50 inch area. This area (0.25-0.50 inches T-bar) was of particular interest due to the nonlinear relationship noted between cost and T-bar (6:31). T-bar values below 0.25 inches have proven to be very hard to machine, thus negating any cost savings due to weight reduction (27).

Figure 6 indicates the increments used in varying the values of input variables. Rib spacing increments and stringer types were the same as those used in the research by Christensen and Evans. Wing loads were varied from 250,000 pounds to 750,000 pounds in steps of 50,000 pounds to generate T-bar values in the 0.25 to 0.50 range. Some values of T-bar occurred outside the 0.25 to 0.50 boundaries due to the fact that T-bar values change internally in VDEP based upon wing cross-sectional area, structural elements, and loading (21). Stringer spacing, total weight,

and total cost are generated automatically based upon the input variable values.

Statistical Analysis

After the data had been generated it was analyzed in the context of total cost prediction. Parametric statistics were used to unmask the relationships between the independent variables and total cost. As noted previously, earlier research indicated that the relationship between T-bar and total cost in the 0.25 to 0.50 inch area appeared to be nonlinear. To verify/nullify this assumption,plots of T-bar with total cost for the twenty-four combinations of rib spacing and structural type were made. Visual inspection of these plots were made to identify linear relationships. Log-log data plots and bivariate curve fittings were made to verify nonlinearity between the dependent and independent variables. Multiple regression analysis was performed for three randomly selected data sets using the subprogram Regression available in the Statistical Package for the Social Sciences (SPSS).

Multiple regression is a technique to analyze the relationship between a dependent or criterion variable and a set of independent or predictor variables. In our research this technique was more appropriate than other techniques, such as analysis of variance, because it described in numerical terms the extent of relationship

between the dependent variable (total manufacturing cost) and independent variables (20:321).

Behind the use of multiple regression is the assumption that the variables are measured on an interval or ratio scale. All of the independent variables in this research effort met this requirement except for stringer type (L_1). Stringer type was not used in multiple linear regression because from examination of data plots no one stringer type demonstrated better linear relationships.

Using SPSS subprogram Regression the user can specify forward (stepwise) inclusion. In this method the computer will enter variables into the mathematical model in single steps. The new (incoming) variable not already in the model which decreases unexplained variance most will enter at each step. Variance in this case is a measure between the actual value of the dependent variable from VDEP output and the predicted value (20:345).

At each step the significance, how well the actual outcome was predicted, is indicated by an F statistic. The F statistic is the ratio of explained variance to unexplained variance. By using a table of values for this statistic the statistical significance of the relationship between the dependent and independent variables can be ascertained. A significant relationship indicates that at least one of the independent variables is significant in the prediction of the dependent variable.

Assumptions and Limitations

Assumptions

Throughout this research effort certain assumptions have been made:

1. VDEP equations and algorithms have been regarded as accurate. The VDEP model has been tested using B-52, F-111, and DC-10 data. In each case the results obtained were considered highly accurate in comparison with actual cost data (27).

2. The data base correctly reflects an actual DC-10 wing. The data were extracted from reports on the DC-10 aircraft by personnel in the Preliminary Design section of AFFDL.

3. Performance/safety criteria were not exceeded or violated in generating cost and weight data. The VDEP model will generate only structurally sound designs (27).

Limitations

Limitations which must be noted in the use of any results from this study are:

1. The VDEP model uses cost figures in 1977 dollars. Conclusions about other years must be made only by use of appropriate financial techniques.

2. VDEP provides cost and weight data for the 200th aircraft structure. Generalizations to other than the 200th aircraft must be made cautiously.

CHAPTER III

DATA ANALYSIS

Introduction

In this chapter the results of several techniques for analyzing the VDEP data are discussed. The data were first plotted for a visual picture of interrelationships. General trends were identified in the graphs which were then investigated using log-log data plots, curve fitting programs, and multiple linear regression. The inner workings of VDEP were studied to examine limiting variable relationships in the program. Finally, a more detailed computer printout from VDEP resulted in significant findings concerning model validity.

Cartesian Data Plots

After obtaining numerical values from VDEP for the dependent variable (total manufacturing cost) and independent variables (skin thickness, stringer spacing, and actual weight) graphs were developed for each combination of rib spacing and stringer type. These twenty-four graphs are included in Appendix D. The reader should note that the scaling is different for each horizontal axis and also varies between graphs. Increasing loads from 250,000 to

750,000 pounds are annotated starting at the left end of a graphed line and ending at the right.

The data plots were used as a first step in data analysis. By visual inspection no mathematical relationship seemed apparent. All graphs exhibited erratic jumps in cost, both positive and negative, for comparatively small increments of change in the independent variable. As in the previous study by Christensen and Evans, total manufacturing cost decreased with widening rib spacing. Whereas they found separate jay and integral blade to be the lowest and highest cost stringer types respectively, our graphs did not exhibit any stringer type as having a lower cost for a given rib spacing.

Our graphs have two general areas of inflection (peaks or valleys)--at 300,000 pounds and 650,000 pounds total wing load. It is interesting to note that minimum cost occurred most frequently at the 300,000 pound wing load. However, in rib spacings of 26 and 36 inches for integral tee and integral zee, the minimum cost appeared at a wing load of 650,000 pounds. Taken literally, this would mean that the load on the wing or amount of weight the wing could lift should be increased from the minimum of 250,000 pounds to 650,000 pounds to achieve least manufacturing cost. Intuitively this is not rational as heavier wing loads require larger structural members, larger amounts of

material, and cost more to manufacture, within the limits of material/fabrication and assembly cost tradeoffs.

Two areas of added concern came from study of the data plots. Stringer spacing became constant for increased increments of wing loading on some of the graphs, graphs where rib spacing is 26 inches for all stringer types. There were several graphs where a line would cross over itself in plotting a relationship. A good illustration of this can be seen on page 61, Appendix D, where the graph of rib spacing is 26 inches and stringer type is separate jay for the first four loadings.

Discussions with officials at the Air Force Flight Dynamics Laboratory (AFFDL) yielded two possible reasons for the marked jumps in manufacturing cost:

1. The program itself is structured to increase structural variable values by large increments as certain limiting relationships are met.

2. The model itself is not operating properly in the range under consideration; T-bar values between .025 and .50 inches (18).

A detailed study of the program was undertaken to determine limiting mathematical relationships causing jumps in values of the independent variables under study. However, this effort proved fruitless due to the complexity of the over fifty functionally independent subroutines (8:3-2).

Log-log Plots

To further analyze possible relationships that might not be visually apparent, the data were plotted using a log-log scale. These plots would give an indication whether the data follow a power function relationship:

> If the plot of experimental data upon a Cartesian chart having uniform scales reveals a curve that might possibly belong to the family of curves represented by the form $y = bx^m$, verification of this fact can be made by plotting the data on a chart having logarithmic scales for the x and y axes, in which case the plot of the data should lie approximately on a straight line [13:200].

Appendix E shows the data from Christensen and Evans study plotted on log-log paper. These plots were taken from view-graphs constructed by AFFDL. The nearly linear steep lines for all stringer types indicate a strong power function relation between T-bar and cost as well as T-bar and weight. In contrast to these plots, the data from this study are shown plotted on log-log scales in Appendix F. Unlike the plots using Christensen and Evans data, these plots demonstrate less defined (not as linear) and less significant (less steep) power relationships.

Line Segment Analysis

To check for possible mathematical functions describing segments of the graphs, the Texas Instrument Calculator Model 58 with the Bivariate Curve Fitting program was used. This program can be used to fit three types of curves to data input--exponential, power, and logarithmic. The

equations for these curves are transformed internally into the form indicated in Table I.

Table I

Internal Data Transformations in the Bivariate Curve Fitting Program

Curve Type	Equation	Transformed Equation
Exponential	$y = be^{mx}$	$\ln y = \ln b + mx$
Power	$y = bx^m$	$\ln y = \ln b + m \ln x$
Logarithmic	$y = b + m \ln x$	same

The Bivariate Curve Fitting program includes routines for determining the correct values for the y intercept, slope, and correlation coefficient (r) (28:5-8 to 5-10).

Segments of the graphs were selected for analysis which visually appeared to present a parabolic relationship (smooth curve) on Cartesian coordinates. The results are summarized in Table II.

The correlation coefficient shown in Table II may vary between the limits of plus and minus one. A plus one would indicate perfect positive correlation whereas a negative one would indicate perfect negative or inverse correlation. A zero correlation coefficient would indicate that no correlation exists between the expected curve values and the actual data points.

Table II

Line Segment Analysis Using the Bivariate Curve Fitting Program

Relation	Stringer Type/Rib Pitch (inches)	Wing Loading (pounds)	Correlation Coefficient for Different Curves		
			Expon.	Power	Log.
T-bar to Cost	Separate jay/46	250-450,000	.7512	.7111	.712
T-bar to Cost	Separate jay/56	250-450,000	-.2934	-.3280	-.3300
Stringer Spacing to Cost	Separate jay/46	250-450,000	.7289	.708	.7099
Stringer Spacing to Cost	Separate jay/56	250-450,000	-.3086	-.3259	-.3279
T-bar to Cost	Int Blade/36	550-750,000	.6416	.6015	.6029
Weight to Cost	Int Blade/36	550-750,000	.6909	.6679	.6694
T-bar to Cost	Int Blade/46	250-450,000	.6522	.6066	.6090
Stringer Spacing to Cost	Int Blade/46	250-450,000	.6299	.6068	.6092
Weight to Cost	Int Blade/46	550-750,000	.7165	.8778	.8803
T-bar to Cost	Int Zee/56	250-500,000	.8030	.7798	.7580
Stringer Spacing to Cost	Int Zee/56	250-500,000	.7848	.7642	.1542
T-bar to Cost	Int Tee/56	250-500,000	.8044	.7641	.7988
Stringer Spacing to Cost	Int Tee/56	250-500,000	.7850	.7643	.7597

A test to determine the validity of the correlation coefficient for the data comparisons was established as follows:

$$\text{Hypothesis tested:} \quad H_0: \rho = 0$$
$$H_1: \rho \neq 0$$

where ρ represents the true correlation coefficient. Let $v = n-2$ where n is the number of sample data points. A t-statistic was computed from the formula:

$$t = \sqrt{vr^2/(1-r^2)}$$

For the examples, v is three except for the last four entries of Table II where v is four due to six data points being plotted.

Substituting the highest correlation factor observed, .88 into the formula for the t-statistic we obtained $t = 3.209$. The 95 percent confidence interval for the t-statistic with 3 degrees of freedom is -3.18,3.18. The correlation at 95 percent confidence is significant. One should note, however, that an r value below .88, for example .87, gives a t-statistic of 3.056 which is not significant at the 95 percent confidence level (28:5-7).

A second point to note is that these particular segments of graphs were selected for what appeared to be the best visual relationship. A high correlation, as in the best example which was an integral blade stringer with 46 inch rib spacing, is only of value if it can be in some way

related to the phenomena observed to explain/predict a future occurrence. This line segment analysis did not yield a significant relationship that could be used in the prediction of cost.

Multiple Linear Regression

Even though the graphed data did not appear to follow a linear relationship, the multiple linear regression analysis subprogram Regression from the Statistical Package for the Social Science (SPSS) was used to verify that no linear relationships did, in fact, exist. Three specific cases were analyzed using the CREATE computer system. These cases were: (1) integral blade at 26 inch rib spacing, (2) separate jay at 36 inch rib spacing, and (3) integral tee at 76 inch rib spacing. The stepwise inclusion method was specified in each case to identify in order the variables which most affected the prediction of cost from the data set. The independent variables presented for inclusion in the model were T-bar, stringer spacing, weight, and wing load. The results of multiple linear regression for the three cases selected are shown in Tables III, IV, and V. After each table an equation is given listing the regression coefficients (B_i) for the "best fit" equation for a straight line through the data points. In each case the F_o value is the program computed F ratio. In each of the tables one of the variables failed to enter the equation. Below the

table the statement "tolerance less than .001" is cited. This means that the portion of the variance of the variable that did not enter is less than .1 percent of the variance already explained by other variables in the equation (20:346).

Table III

Multiple Regression, Cost with T-bar, Stringer Spacing, Weight, and Wing Loading
(L Type = Int Blade, R = 26)

Variable Entry	Name	B_i	F_o
T	T-bar	7820016.366	6.641
S	Stringer Spacing	- 313284.398	3.584
W	Weight	- 190.667	3.413
Constant	---	6918354.798	---

Total wing load did not contribute significantly to the model; less than .001 tolerance.

Equation: $C = 7820016.366T - 313284.398S - 190.667W + 6918354.798$

To test the statistical significance of B_i two approaches may be taken: (1) in isolation, or (2) with M other independent variables. The conservative approach is to test the B_i values simultaneously. To do this an equivalent-alpha level must be computed to conduct the test. Using Bonferroni's approach, equivalent-alpha = $\alpha \div (M + 1)$, where M equals the number of other independent

Table IV

Multiple Regression, Cost with T-bar, Stringer Spacing, Weight, and Wing Loading (L Type = Sep Jay, R = 36)

Variable Entry	Name	B_i	F_o
T	T-bar	5663543.785	3.605
W	Weight	- 151.181	2.740
S	Stringer Spacing	- 173788.508	0.819
Constant	---	4835961.077	---

Total wing load did not enter model; contribution less than .001.

Equation: $C = 5663543.785T - 151.181W - 173788.508S + 4835961.077$

Table V

Multiple Regression, Cost with T-bar, Stringer Spacing, Weight, and Wing Loading (L Type = Int Tee, R = 76)

Variable Entry	Name	B_i	F_o
W	Weight	- 142.332	1.302
S	Stringer Spacing	- 485229.074	4.549
U	Wing Loading	6.431	3.978
Constant	---	7447022.477	---

T-bar did not enter the model; contribution less than .001.

Equation: $C = -142.332W - 485229.074S + 6.431U + 7447022.477$

variables. With an alpha level of .05, the equivalent-alpha value is dependent upon the number of independent variables included in the regression equation (35).

In determining whether the independent variables in the regression equation are statistically significant, the null hypothesis is tested which states that the coefficient of the respective independent variable is zero; the independent variable has no effect on cost:

$$H_o: \; B_i = 0$$
$$H_1: \; B_i \neq 0$$

The critical value (F_c) is found using the F distribution with one upper and n-p (7) lower degrees of freedom. For an alpha level of .05 (95 percent confidence) the equivalent-alpha will be .05/3 = .0167 and $F_{c(1,7,.0167)} = 11.09$. Since none of the F_o values in any of Tables III through V are larger than 11.09, the null hypothesis cannot be rejected and none of the independent variables in the three cases of multiple linear regression are considered statistically significant.

The Bonferroni technique for finding the confidence coefficient for a family of variables in the same equation in actuality gives a lower bound on the true, but often unknown, family confidence coefficient. However, this technique was used for the analysis at hand due to a high degree

of correlation among the independent variables under test (19:147).

Limiting Relationships

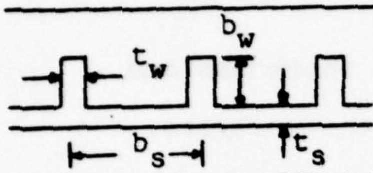
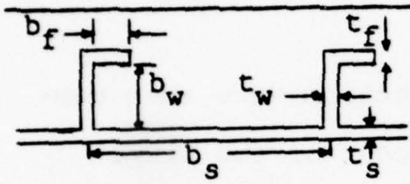
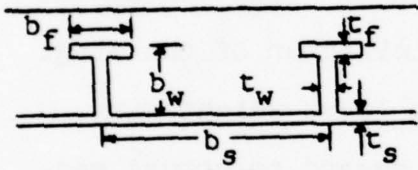
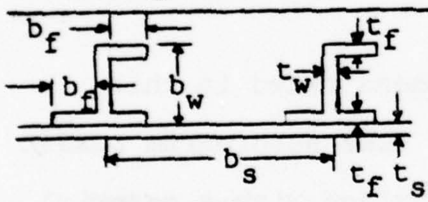
As noted earlier, a very disturbing point encountered in visual analysis of the Cartesian coordinate data plots was that in several cases stringer spacing seemed to reach a limit, staying the same for additional increasing increments of wing loading. Further research into the User's Manual for the VDEP program revealed that limiting relationships involving stringer spacing exist as shown in Table VI. Because the variable values of stringer height and stringer riser thickness were not part of the normal computer output that was being received from VDEP, the print statements were modified to increase the output and give these values (see Appendix H). Values for BW, BS TW, and TS were used to make a scale drawing of the stringer as VDEP designed it. These drawings were structurally feasible and did not overlap or form infeasible stringer shapes.

Subprogram BOXSIZ

The lack of a meaningful relationship between the dependent and independent variables led to a more detailed study of the VDEP model and especially the subprogram BOXSIZ. This analysis resulted in the following:

Table VI

Limiting Values in Stringer/Skin Relationships

Configuration	LType	Allowable Range
 Integrally Stiffened	LType = 1	*BW/BS = 0.30 - 0.60 *TW/TS = 0.80 - 2.00
 Integral Zee	LType = 3	BW/BS = 0.20 - 0.80 TW/TS = 0.50 - 1.00
 Integral Tee	LType = 4	BW/BS = 0.20 - 0.60 TW/TS = 0.70 - 1.40
 "J" Stiffened	LType = 5	BW/BS = 0.20 - 0.60 TW/TS = 0.60 - 1.00

*BW = Stringer Height (inches)
BS = Stringer Spacing (inches)
TW = Stringer Riser Thickness (inches)
TS = Skin Thickness (inches)

(8:2-13)

1. The design of the wing was accomplished on a cross sectional basis with each section being sized by:

a. Analyzing the structure as it is defined by input data.

b. Predicting the new skin thickness and stiffener area based on the results of the analysis.

c. Re-analyzing the structure as predicted in b.

2. The costs for each wing section were then computed and totaled to find the entire cost of the wing. This results in an optimum wing design on a section by section basis but not on an overall optimization of the wing. In addition, this method results in a least weight wing, designed section by section, without regard to actual construction methods.

The design methodology is demonstrated in this example using the computer output of VDEP subprogram BOXSIZ from a run accomplished for a wing surface with a material type of Aluminum 2024-T6, a surface load of 250,000 pounds, integral zee stringer type, and a rib pitch of 26 inches. The spar data for the swept axis is:

1. Front spar = 17 percent

2. Rear spar = 68 percent

Using this data with the information presented in the Rib Data printout, see Appendix G, and subtracting the front spar percentage from the rear spar percentage, there is

51 percent of the full chord available at each rib station for calculation of stringer spacing. The stringer spacing is designated by BS in Appendix H and is divided into the chord available, 51 percent of the full chord, to determine the number of stringers at that rib. For example, at ribs numbered 1 and 41 respectively of the compression cover, the calculation for determining the number of stringers is:

<u>Rib Number 1</u>

Full chord	420.93 in.
	<u>x .51%</u>
	214.67 in.
BS	<u>÷ 5.26 in.</u>/stringer
	40.81 stringers

<u>Rib Number 41</u>

Full chord	134.27 in.
	<u>x .51%</u>
	68.47 in.
BS	<u>÷ .83 in.</u>/stringer
	82.50 stringers

This results in 40 stringers at rib number 1, wing root; and 82 stringers at rib 41, the last rib before the tip of the wing. These calculations can be carried out for each rib station and would show that the number of stringers is not constant at each rib. At rib number 26, for the compression cover and the tension cover, the number of

stringers starts to increase and continues to increase until the tip of the wing is reached. See Appendix I for an example of calculated stringers per rib per wing.

VDEP prints out the total number of stringers per wing as being the average of the number of stringers at the wing root and the last rib. This average number of stringers is then used to calculate the total weight of the stringers in the wing. Analysis of the output shows that in order to obtain the least weight for that wing section the number of stringers is different at each rib. This difference in the number of stringers at each rib used for least weight construction and the number of stringers used to calculate the total weight of stringer material in the wing results in weight being determined by one set of data and the cost of the wing being calculated from another set of data.

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

Introduction

The major thrust of this research effort was to determine the algorithms for use with VDEP in order to optimize the cost estimation of aircraft wing structures. This effort focused on the T-bar range of 0.25 to 0.50 inches. Within this range the VDEP model produced costs and design results which when analyzed could not be used to produce an algorithm for costs or a feasible design. The conclusions drawn from this study do not answer the research questions which guided it.

As shown in Chapter III the data analysis did not result in a usable relationship between T-bar and cost. This lack of a relationship led to an analysis of the VDEP model subprogram BOXSIZ. Analysis showed that the wing was designed section by section and that subprogram BOXSIZ determined the least weight design for each section. These sections were then summed to obtain the least weight wing.

Each section had a different number of stringers at each rib. The stringers in each section were changed in order to simultaneously meet performance criteria and the least weight construction criteria. Another value for

the number of stringers in the wing was calculated by the average of the number of stringers at the wing root rib and the last rib of the wing. This number was then multiplied by a constant value for material used in construction to obtain the weight of the stringers in the wing. This difference in the number of stringers at each rib for least weight construction and the number of stringers used to calculate the total weight of the wing results in the weight and design of the wing being determined by one set of data and the cost of constructing that wing being calculated by another set of data.

While this method of designing a wing in sections is an asset to modeling on a computer, the result in this case is unacceptable. C. H. Latimer Needham stated that ". . . it is important that the stringers should be continuous [17:237]." Interviews with Dale Nelson and Richard Mueller of Air Force Flight Dynamics Laboratory reinforced Needham's statement and confirmed that the VDEP BOXSIZ wing design was not correct (18). Gerard's analysis of stringer panels assumes that stringer spacing is constant throughout the panel and that for a constant stringer width close stringer spacing is required for panels of minimum weight (9:48). VDEP changed the number of stringers in almost every section; therefore, they are not continuous. VDEP also changed stringer spacing in almost every section.

Conclusions

The VDEP subroutine BOXSIZ is not performing a proper structural synthesis for the aerodynamic surface of the wing. Each subprogram of VDEP that uses output data from BOXSIZ is subject to error.

The relationship between T-bar and cost in the T-bar range of 0.25 to 0.50 inches is not definable as a design parameter in developing a cost optimization algorithm with VDEP. Previous research indicated a relationship between the independent variables and cost. The graphs in Appendix E are based on that research and indicate a strong case for linearity. The research also indicated that in the lower values of T-bar a power function may be the best relationship between T-bar and cost (6:28).

This relationship could not be established by our follow-on research. As shown in Appendices D and F the graphs do not portray a linear or usable power relationship. Statistical analysis does not indicate a relationship between the independent variables and cost.

The subroutine BOXSIZ fails to properly determine the weight of the wing and the cost of manufacturing the wing. The discovery of an improper structural synthesis within the BOXSIZ subroutine explains the undefined relationship of the variables and invalidates the VDEP model. The model does not function as a correct estimator of airframe manufacturing costs.

Any studies of VDEP or conclusions drawn from it should be re-evaluated with respect to this finding. The value of VDEP as a design tool cannot be measured until the entire program is checked for other errors and corrected. This effort is estimated to take as much as 20 man years to accomplish (27).

Corollary Conclusions

Based on the analysis of the data as explained in Chapter III, the researchers believe that the use of VDEP as a basis for developing algorithms to assist design engineers and cost analysts should not be continued.

As shown in Appendix J the VDEP BOXSIZ subprogram for structural synthesis, Contract NAS 2-5718, has not been carried forward in subsequent NASA or Air Force contracts. The lack of this subprogram will prevent it from generating erroneous data for more advanced models; however, this research shows that each model must be verified. Without verification the model and its output must be suspect as to validity, and conclusions drawn from the non-validated model must also be suspect.

Summary

This research attempted to further clarify relationships between cost and design parameters in the NAS 2-5718 VDEP model, using DC-10 wing data. Definite relationships could be used to further the development of

algorithms which would assist VDEP in designing an optimum cost aircraft structure. In using the VDEP program it was determined that the program did not perform a proper wing structural synthesis in the subprogram BOXSIZ. Any conclusions or studies performed utilizing VDEP, NAS 2-5718, should be re-evaluated with respect to this finding.

Recommendations for Further Research

1. As depicted in Appendix J, the VDEP model for BOXSIZ is not used in the follow-on models. The follow-on models must be verified to insure that design criteria, structural integrity, and construction criteria are realistic. Estimating relationships are as valid as the data comprising them and the models in which the data are used. Research in the form of validation of the models must be accomplished to insure realistic relationships can be defined.

2. Feasibility studies should be continued to develop optimization algorithms for aircraft design at minimum cost. Studies to develop or discover design/cost relationships should be continued. This will aid design engineers, cost analysts, and planners in designing optimum cost aircraft structures.

3. Future studies using the VDEP model (NAS 2-5718) to develop a cost optimization algorithm should not be attempted.

APPENDIX A

VEHICLE DESIGN EVALUATION PROGRAM (VDEP)

The Vehicle Design Evaluation Program (VDEP)[1] is intended to be used as a preliminary design analysis tool to enable the user to rapidly perform tradeoff studies involving fatigue, fracture, static strength, weight, and cost. The total computer program is broken down into five modules (see Figure 7), the program driver, vehicle sizing, structural synthesis, detail part definition, and cost synthesis. Output may be selected from a complete and fully detailed version or a summary version based on the input data.[2]

The program driver calls the program modules in proper sequence and initializes variables. It is appropriately titled in that it drives the total program.

The vehicle synthesis module sizes the aircraft, performs a balance analysis, distributes the area, and displays a planform view along with other pertinent design data, such as weight statements, center of gravity (CG) data, and general geometric data. This program includes a curve plotting routine which allows the user to perform

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[1]For this research effort, VDEP was used in the batch mode. The interactive graphics package was not used. All VDEP processes described herein were essentially the same.

[2]This appendix is cited as it appears on pages 38-43 of thesis LSSR-30-77A. See Bibliography reference 6.

PROGRAM DRIVER — Calls program modules in the proper sequence and initializes variables.

↓

VEHICLE SYNTHESIS — Generates vehicle size, weight, and balance for tradeoff study evaluations during standard preliminary design methods.

↓

STRUCTURAL SYNTHESIS — Generates detail geometry, loads, and optimum weight data for primary structural components as a function of materials and construction type.

↓

DETAIL PART DEFINITION — Generates a list of detail parts and processes as a function of the selected option. Computes actual and material weight of each detail part.

↓

COST SYNTHESIS — Generates manufacturing cost as a function of standard hours and material cost. Generates total program cost and return-on-investment as a function of tooling, engineering, and manufacturing costs.

↓

OUTPUT

Figure 7. VDEP Program Modules

parametric tradeoff studies and obtain printouts for further evaluation. These tradeoff studies are possible at several levels of consideration. For example, weight and cost data can be related directly to key system parameters at the vehicle mission level such as payload, speed, range, and landing field length requirements. At the vehicle configuration level, data can be related directly to surface areas, spar, sweep, taper, etc., and fuselage length, slenderness, etc. At the major component level, comparisons can be made between different materials, modes of construction, and detailed part make-up. Tradeoffs can be made at each of these levels to determine the overall vehicle weight and cost sensitivities. This enables the designer to refine the proposed aircraft design to a high degree of detail. Thus, engineering functions are able to gain insight into the cost effectiveness of alternative aircraft system designs and to determine the impact of more detailed engineering alternatives with respect to any particular aspect of a design.

The structural synthesis module provides detailed geometry loads and weight data for the primary structural elements associated with the aerodynamic surfaces and the basic fuselage structural shell. Structural synthesis provides a means of descriptively designing structural components to fulfill specified requirements of strength and geometry. This program uses a multi-station synthesis

process. The basic philosophy of this process is that a set of structural elements can be determined which will satisfy the design criteria at each station and that the aggregation of these elements will result in a reasonable representation of the structure. It is the structural synthesis portion of the total computer program which contains the subroutine to add or subtract material from the structural elements in an attempt to produce a minimum weight structure. The purpose of this optimization redesign process is to change a given design to produce a lighter weight design while satisfying performance constraints such as minimum gages, positive margins of safety, etc.

The part definition program utilizes the output from the structural synthesis module to derive all the detail parts sufficient to construct the complete assembly of the aircraft. The actual parts weights and the weight of the raw material to be purchased are also derived as part of this module based on the computed part geometry.

The part definition module is coupled with the cost synthesis program through the manufacturing cost analysis. The manufacturing cost analysis consists of a definition of manufacturing processes associated with each part, the standard labor hours, and the material weight. A list of shop operations is called out with each detail part, and a series of equations associated with each operation is used to compute the shop hours (standard hours) necessary to

make the part. By applying the appropriate labor rates to the calculated hours, the direct and indirect manufacturing labor costs are found. The material costs are computed based on the amount of material required to manufacture each part. Additional cost analysis includes tooling, engineering, total program, and return-on-investment costs.

Tooling costs are computed as a function of the number of basic tool manufacturing hours, initial and sustaining hours are derived as a function of the number of dissimilar parts to be produced, the average number of tools required per dissimilar part, and the average number of hours required to produce each tool.

Engineering costs are computed based on the number of manhours necessary to perform the various tasks associated with the development and production of the aircraft. Initial engineering hours are broken down and distributed among the various engineering disciplines based on studies made of historical data.

A learning-curve approach is used to derive costs of a given unit or lot as a function of the first unit cost. Engineering plus the other mentioned costs comprise total program costs. Another area, included for commercial operations, is a return-on-investment cost.

Each of the five modules mentioned above has its own input data requirements. Values that are generated in one module are used as inputs to other modules. This makes

possible the generation of data within the program which is difficult or impossible to obtain during aircraft preliminary design. Any time the user desires to set the entire program back to the original data, it can be accomplished without having to set each parameter to its initial state individually. This allows the user to perform a completely different tradeoff study utilizing initial input data plus new changes.[1]

[1]The content of Appendix A is extracted from the user's manual for VDEP-II, Computer Program to Assess Impact of Fatigue and Fracture Criteria on Weight and Cost of Transport Aircraft, General Dynamics, Convair Division, San Diego CA, September 1974.

APPENDIX B

DEFINITIONS

Algorithm.

> A set of procedures or logical steps necessary to calculate and modify the input data values to obtain the answers. It is the development of a logical approach to a problem [24:4].

Cost (C). An amount or quantity of money which is given up (paid) to purchase the specified goal or objective, which in this case is an aircraft wing.

Load (U). The amount of stress, measured in pounds, that is placed on an aircraft structure.

Parameter. A statistical term relating to an arbitrary constant which characterizes, by each of its particular values, some particular member of a system or population (32:1638).

Performance. (1) As it applies to an aircraft, performance means a prespecified set of parameters; such as, speed, range, takeoff and landing ground roll, and turn radius. (2) Pertaining to aircraft structure, the ability of a given structural type and/or material type to meet structural requirements as they contribute to overall aircraft performance characteristics (27).

Rib Spacing (R). Average distance in inches between the stiffening element for the box that is the structural load carrying member (27).

Stringer Spacing (S). Average distance between the stiffening elements for the skin cover of an aircraft wing (27).

T-bar (T). Wing area spread over distance to give an average thickness of the aircraft wing skin (27).

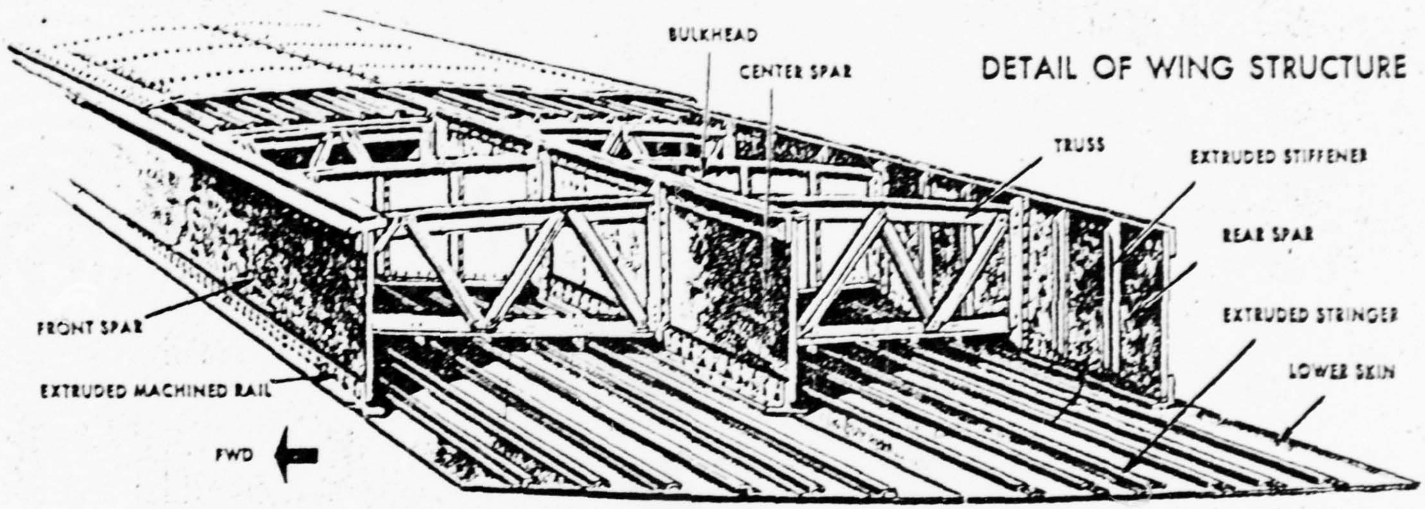
Weight (W). Measurement in pounds of the material usage to construct the final product, a DC-10 wing.

Wing. The lift producing appendage to an aircraft fuselage. It is limited to the basic wing structure by excluding wing attachments such as flaps, ailerons, engines, and landing gear.

APPENDIX C

PICTORIAL VARIABLE PRESENTATION

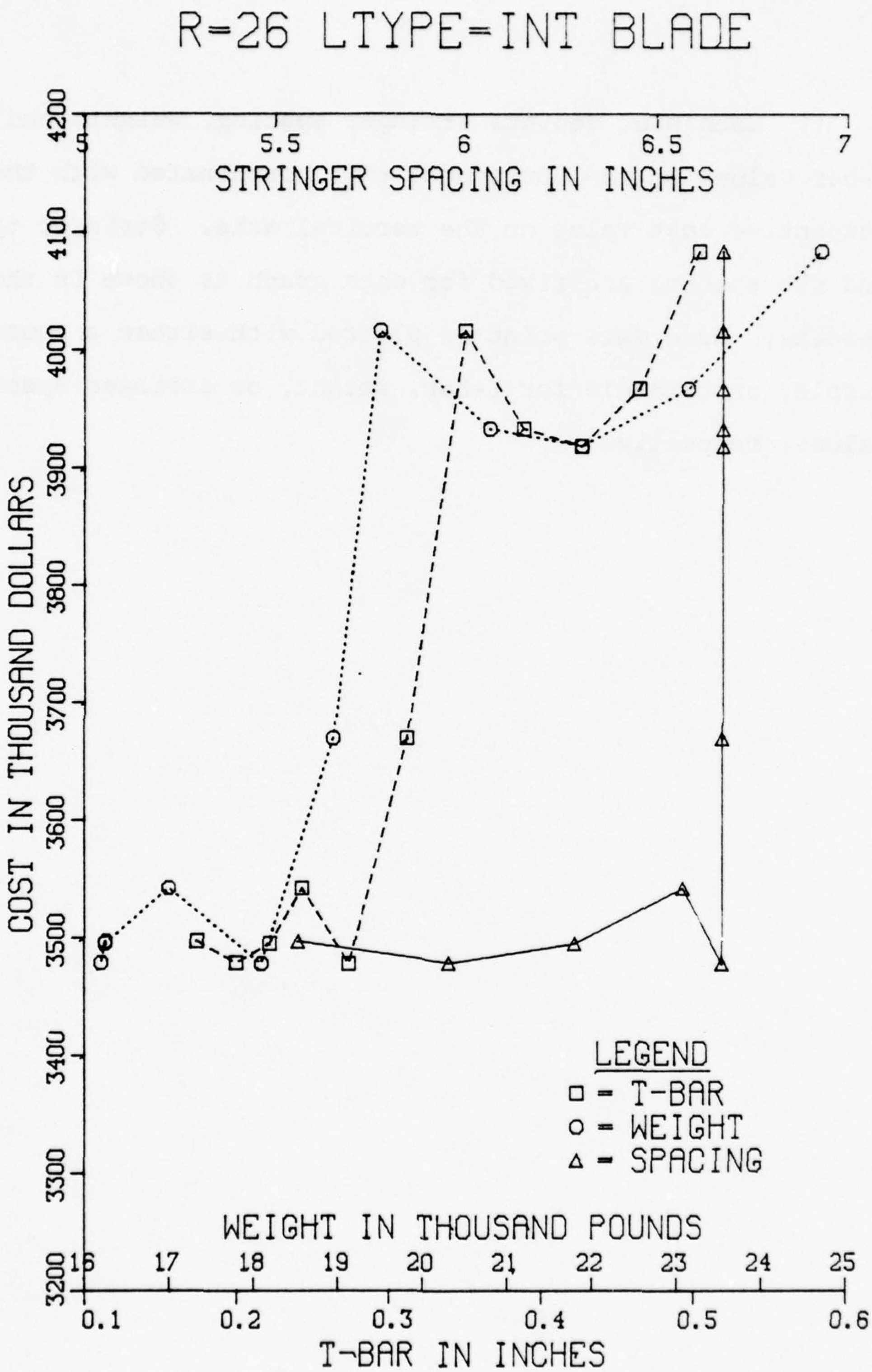
DETAIL OF WING STRUCTURE



APPENDIX D

CARTESIAN COORDINATE DATA PLOTS

Each plot depicts stringer spacing, weight, and T-bar values on the horizontal axis coordinated with the respective cost value on the vertical axis. Stringer type and rib spacing are fixed for each graph as shown in the heading. Each data point is plotted with either a square, circle, or triangle for T-bar, weight, or stringer spacing values, respectively.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5.5
6
6.5
7
COST IN THOUSAND DOLLARS
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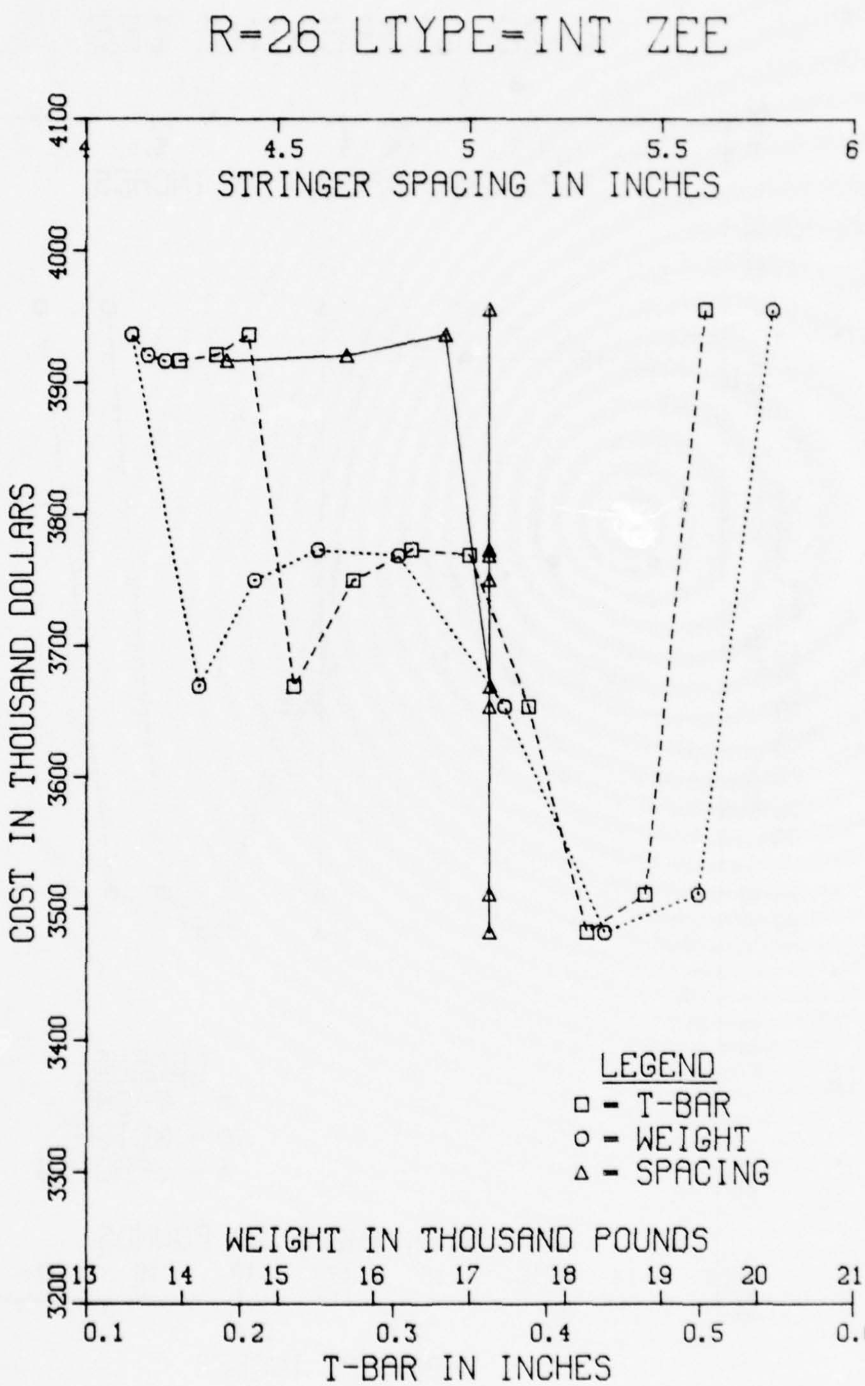
4100
4000
3900
3800
3700
3600
3500
3400
3300
3200
LEGEND
□ = T-BAR
○ = WEIGHT
△ = SPACING
WEIGHT IN THOUSAND POUNDS
16
17
18
19
20
21
22
23
24
25
0.1
0.2
0.3
0.4
0.5
0.6
T-BAR IN INCHES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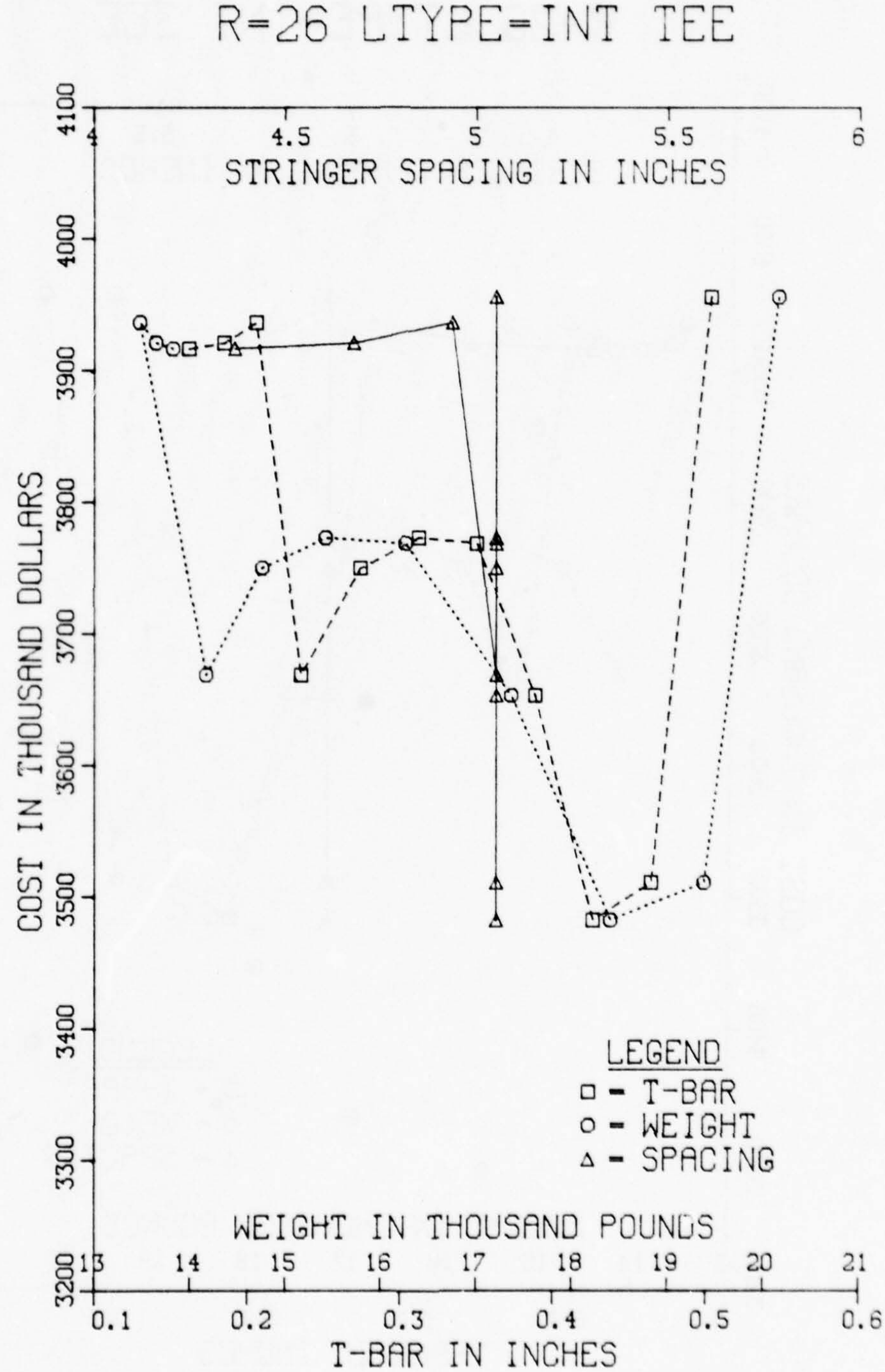
4.5
5
5.5
6
COST IN THOUSAND DOLLARS
3200
3300
3400
3500
3600
3700
3800
3900
4000
4100
LEGEND
□ - T-BAR
○ - WEIGHT
△ - SPACING
WEIGHT IN THOUSAND POUNDS
13
14
15
16
17
18
19
20
21
0.1
0.2
0.3
0.4
0.5
0.6
T-BAR IN INCHES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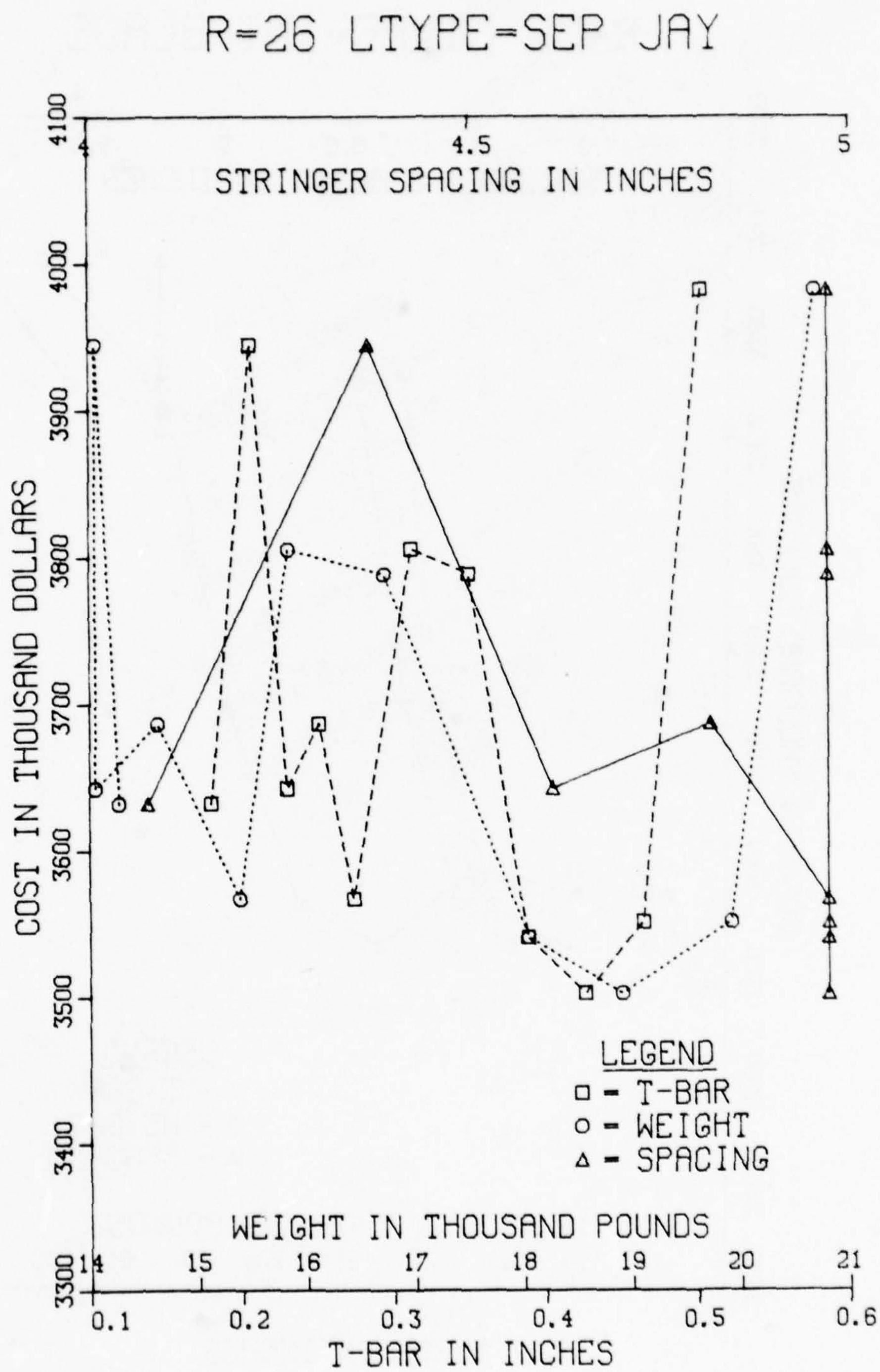
4000
3900
3800
3700
3600
3500
3400
3300
3200
LEGEND
□ - T-BAR
○ - WEIGHT
△ - SPACING
WEIGHT IN THOUSAND POUNDS
13
14
15
16
17
18
19
20
21
0.1
0.2
0.3
0.4
0.5
0.6
T-BAR IN INCHES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5
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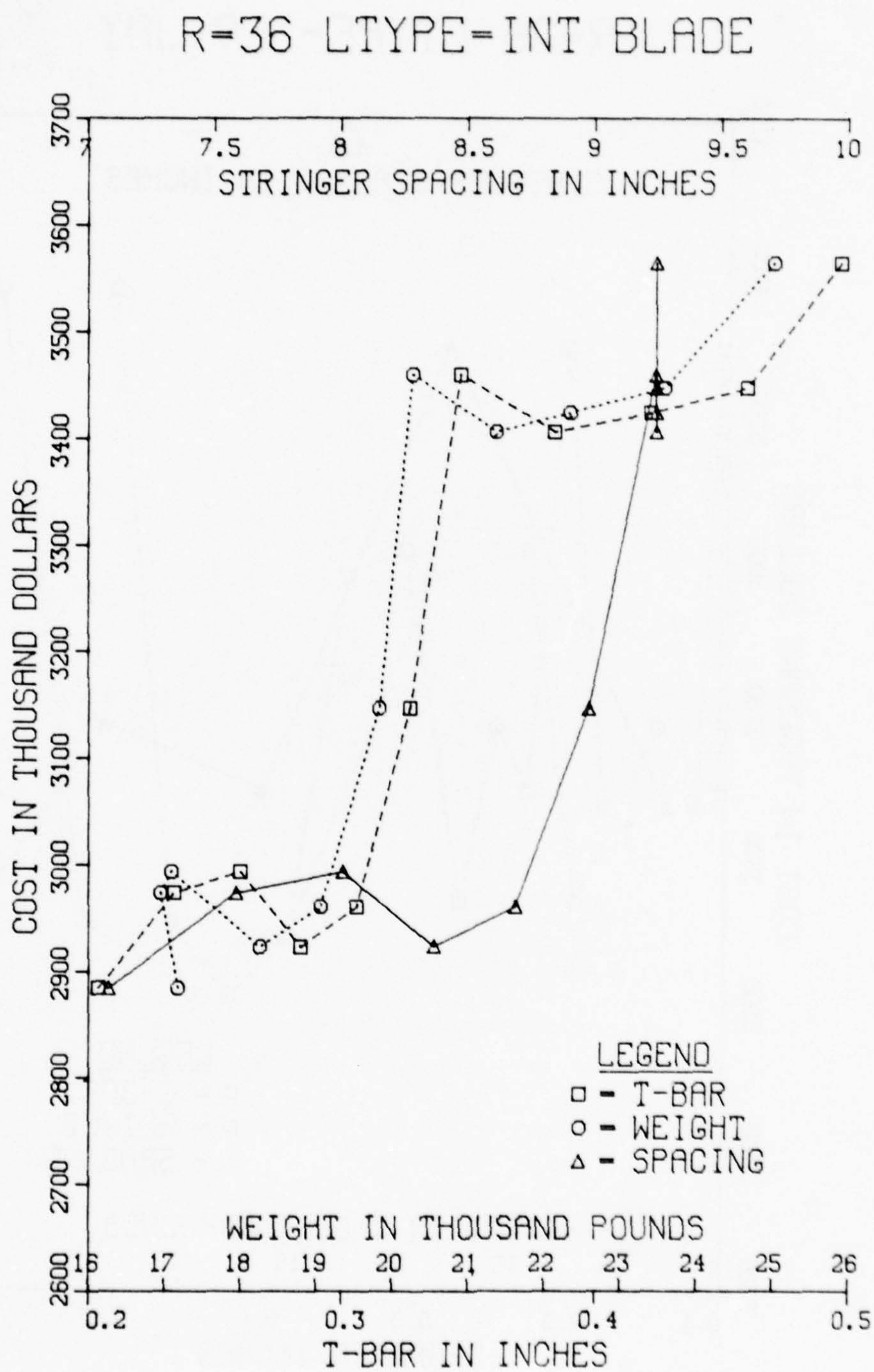
4000
3900
3800
3700
3600
3500
3400
3300
LEGEND
□ - T-BAR
○ - WEIGHT
△ - SPACING
WEIGHT IN THOUSAND POUNDS
14
15
16
17
18
19
20
21
0.1
0.2
0.3
0.4
0.5
0.6
T-BAR IN INCHES



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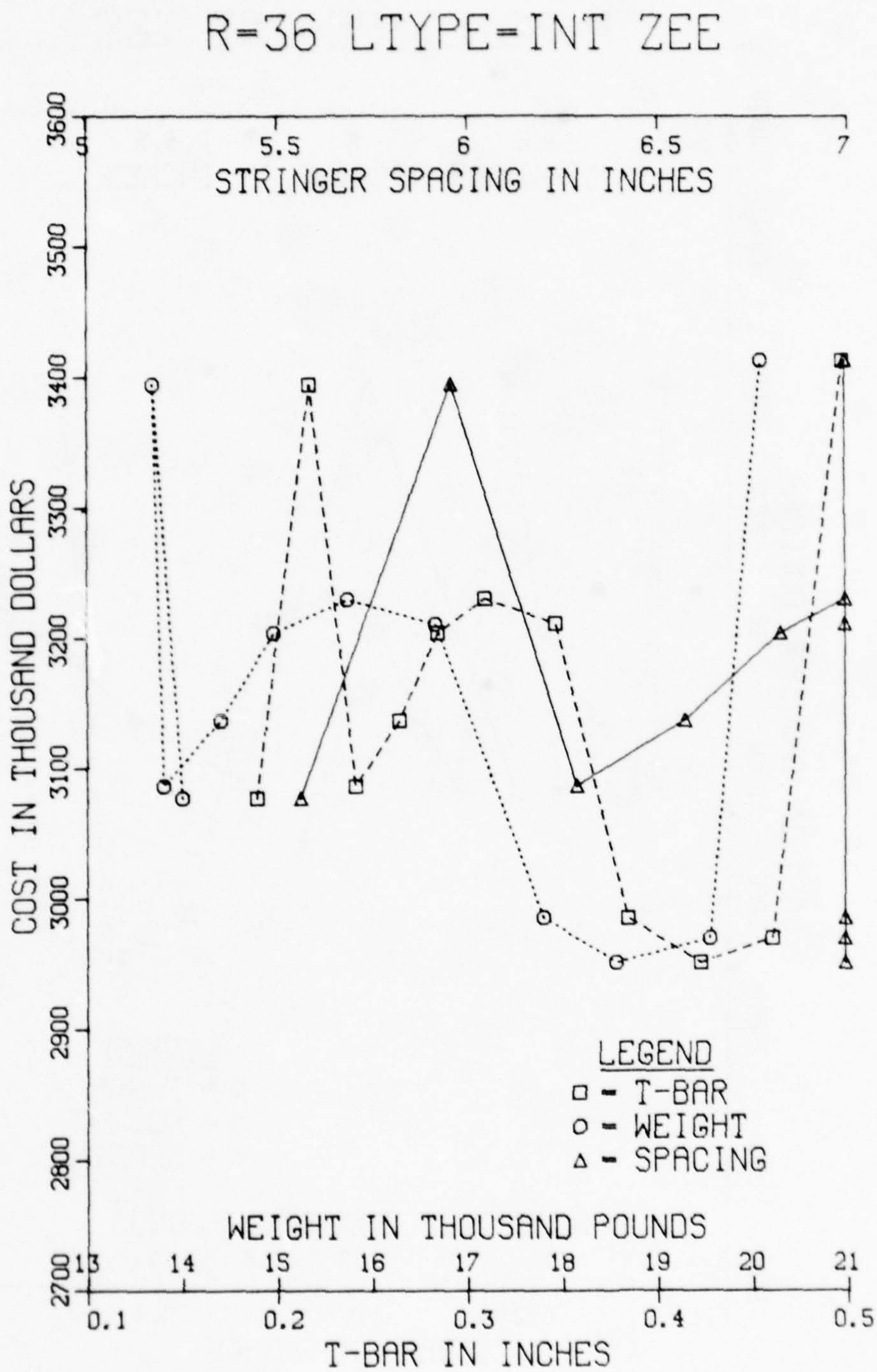
7.5
8
8.5
9
9.5
10
COST IN THOUSAND DOLLARS
2600
2700
2800
2900
3000
3100
3200
3300
3400
3500
3600
3700
LEGEND
□ - T-BAR
○ - WEIGHT
△ - SPACING
WEIGHT IN THOUSAND POUNDS
16
17
18
19
20
21
22
23
24
25
26
0.2
0.3
0.4
0.5
T-BAR IN INCHES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6.5
7
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3500
3400
3300
3200
3100
3000
2900
2800
2700
LEGEND
□ - T-BAR
○ - WEIGHT
△ - SPACING
WEIGHT IN THOUSAND POUNDS
13
14
15
16
17
18
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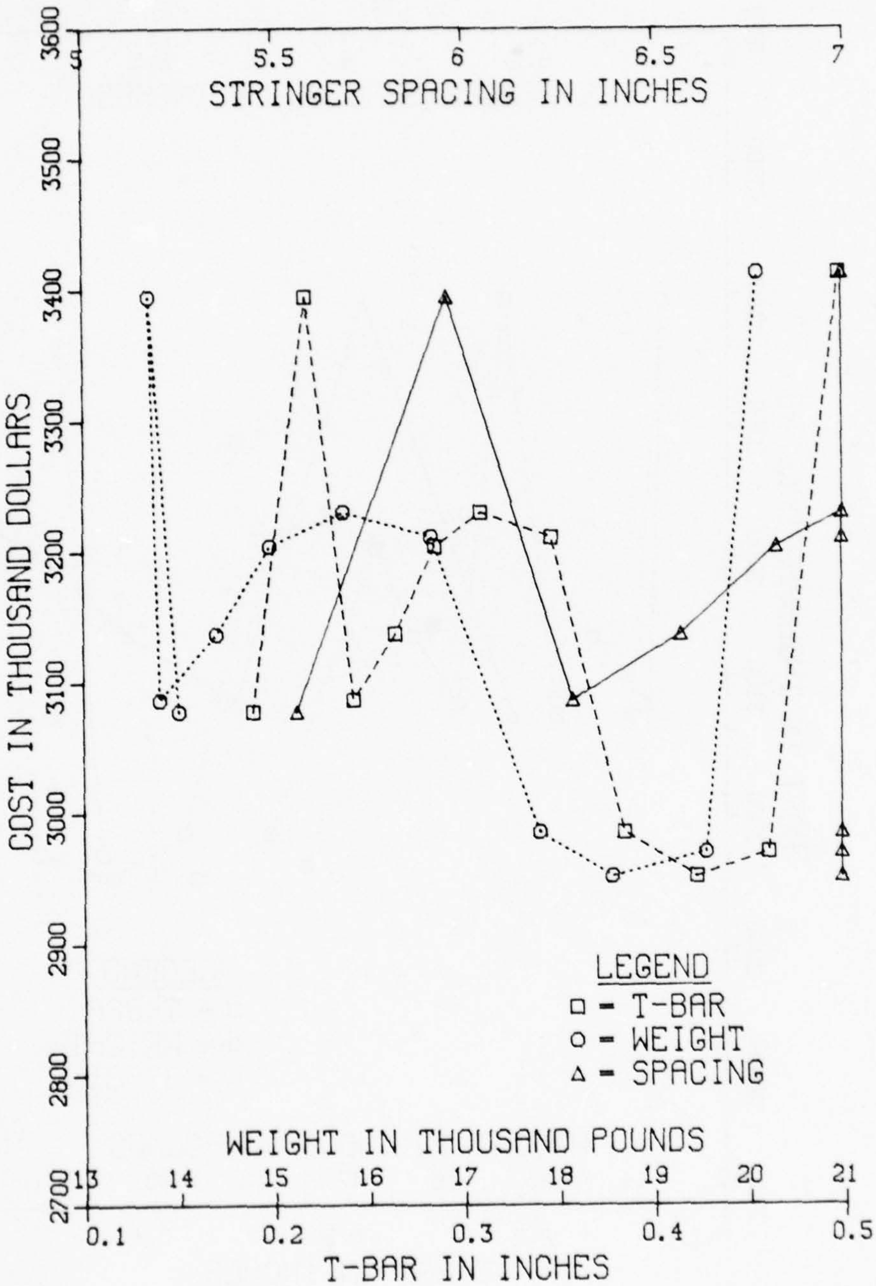
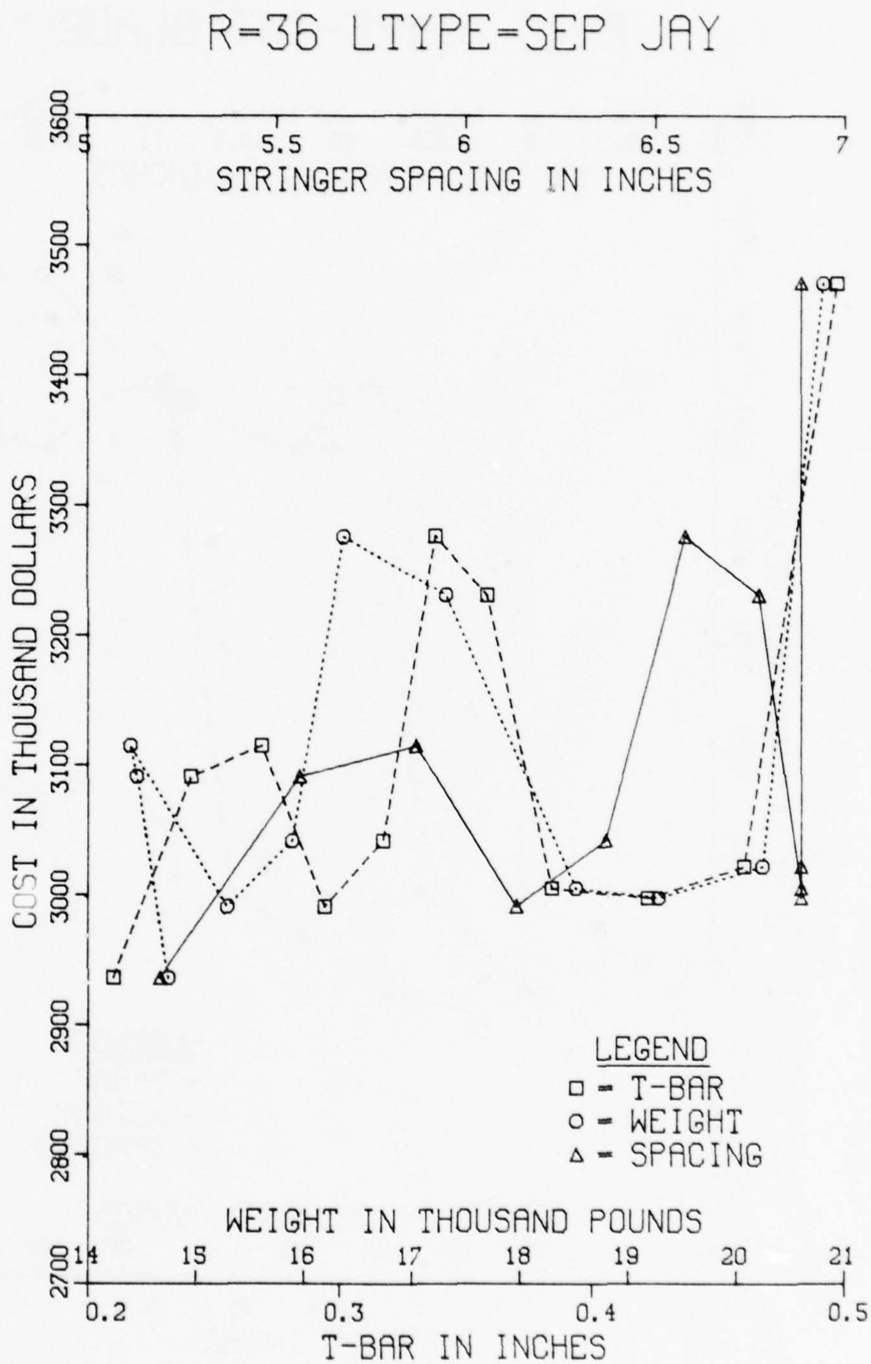
20
21
0.1
0.2
0.3
0.4
0.5
T-BAR IN INCHES

R=36 LTYPE=INT TEE





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6
6.5
7
COST IN THOUSAND DOLLARS
3600
3500
3400
3300
3200
3100
3000
2900
2800
2700
LEGEND
□ = T-BAR
○ = WEIGHT
△ = SPACING
WEIGHT IN THOUSAND POUNDS
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15
16
17
18
19
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21
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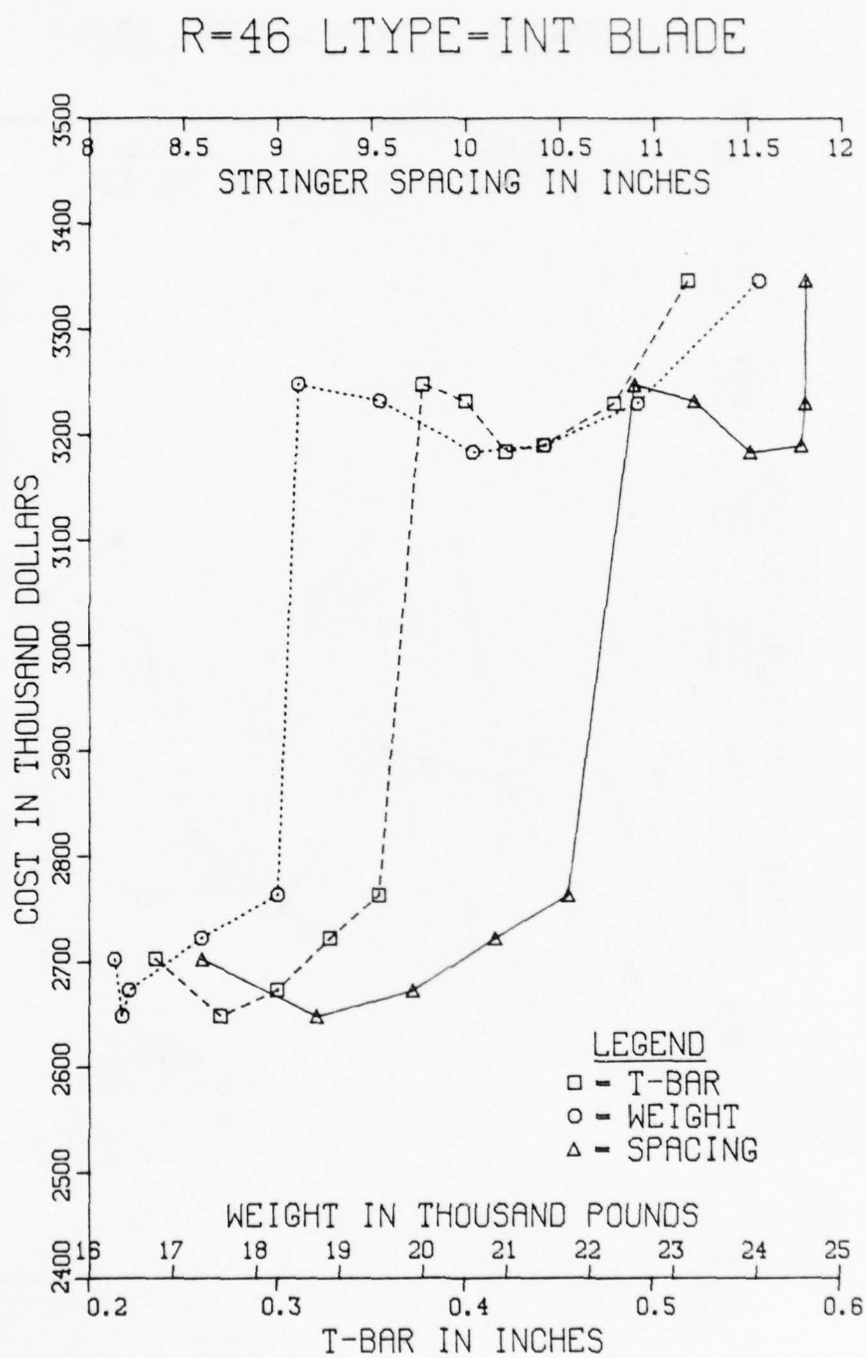
0.3
0.4
0.5
T-BAR IN INCHES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2500
2400
8
8.5
9
9.5
10
10.5
11
11.5
12
STRINGER SPACING IN INCHES
COST IN THOUSAND DOLLARS
LEGEND
□ - T-BAR
○ - WEIGHT
△ - SPACING
WEIGHT IN THOUSAND POUNDS
16
17
18
19
20
21
22
23
24
25
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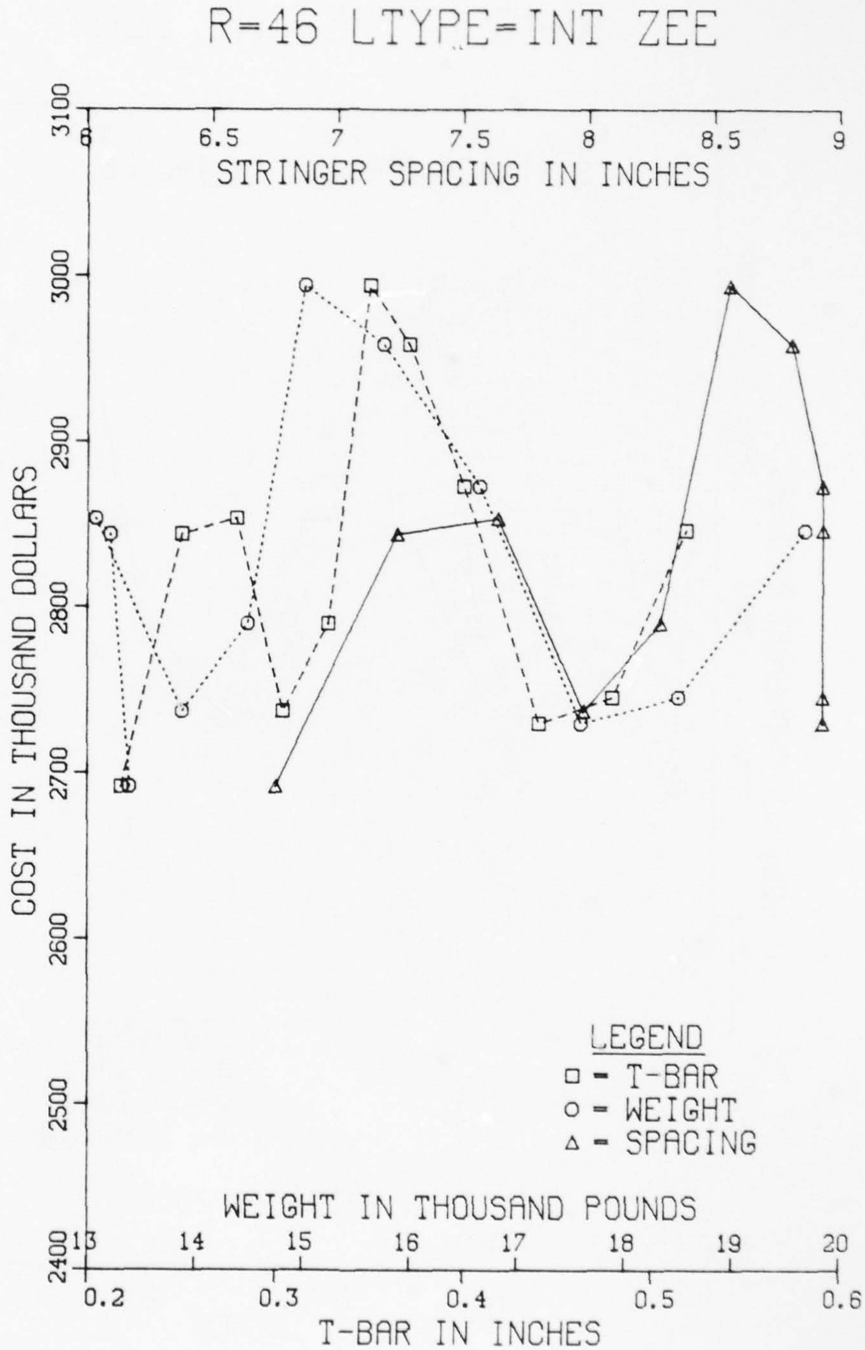
0.4
0.5
0.6
T-BAR IN INCHES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8
8.5
9
STRINGER SPACING IN INCHES
COST IN THOUSAND DOLLARS
LEGEND
□ = T-BAR
○ = WEIGHT
△ = SPACING
WEIGHT IN THOUSAND POUNDS
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16
17
18
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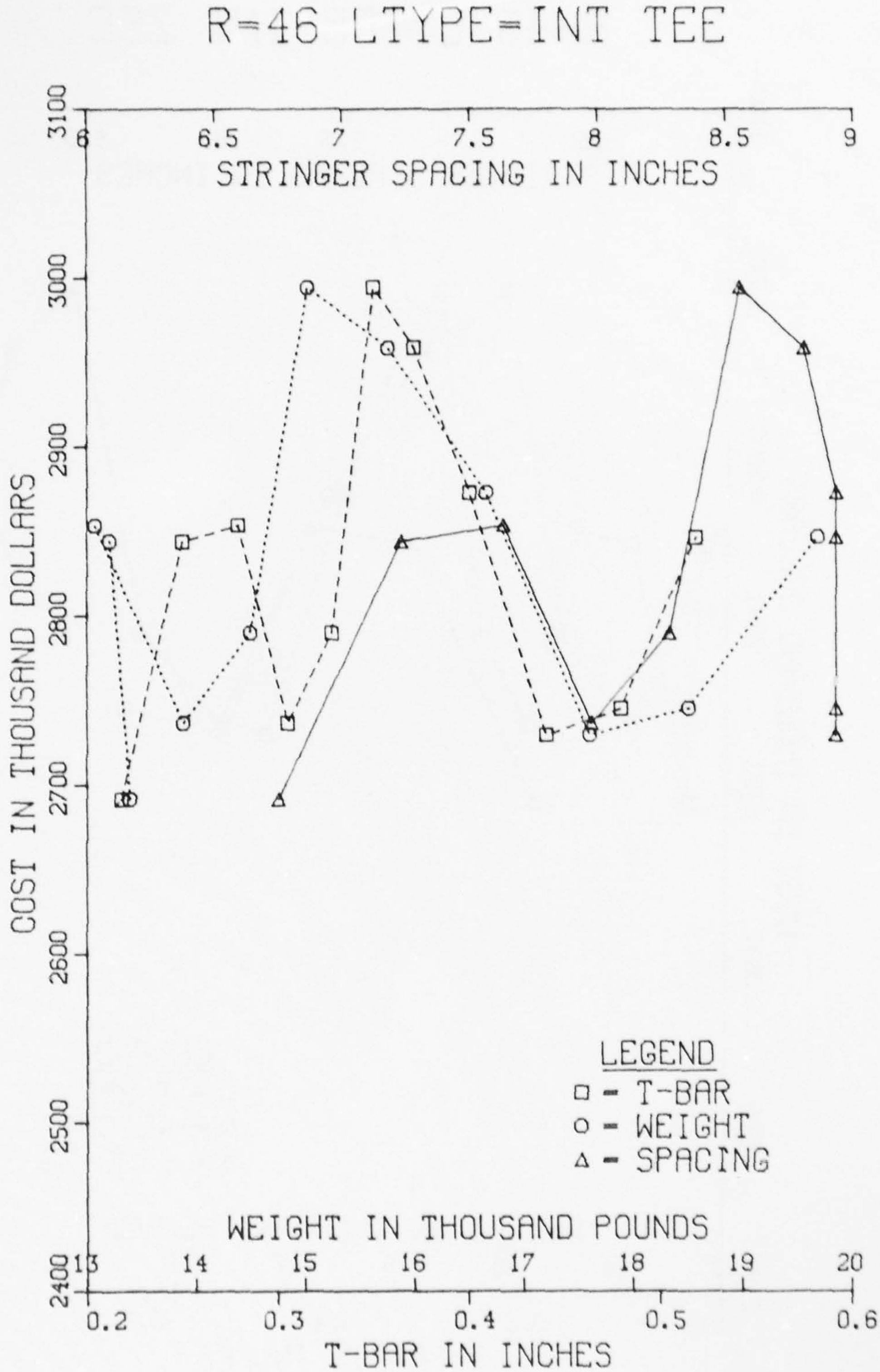
0.4
0.5
0.6
T-BAR IN INCHES



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COST IN THOUSAND DOLLARS
3100
3000
2900
2800
2700
2600
2500
2400
LEGEND
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○ - WEIGHT
△ - SPACING
WEIGHT IN THOUSAND POUNDS
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0.6
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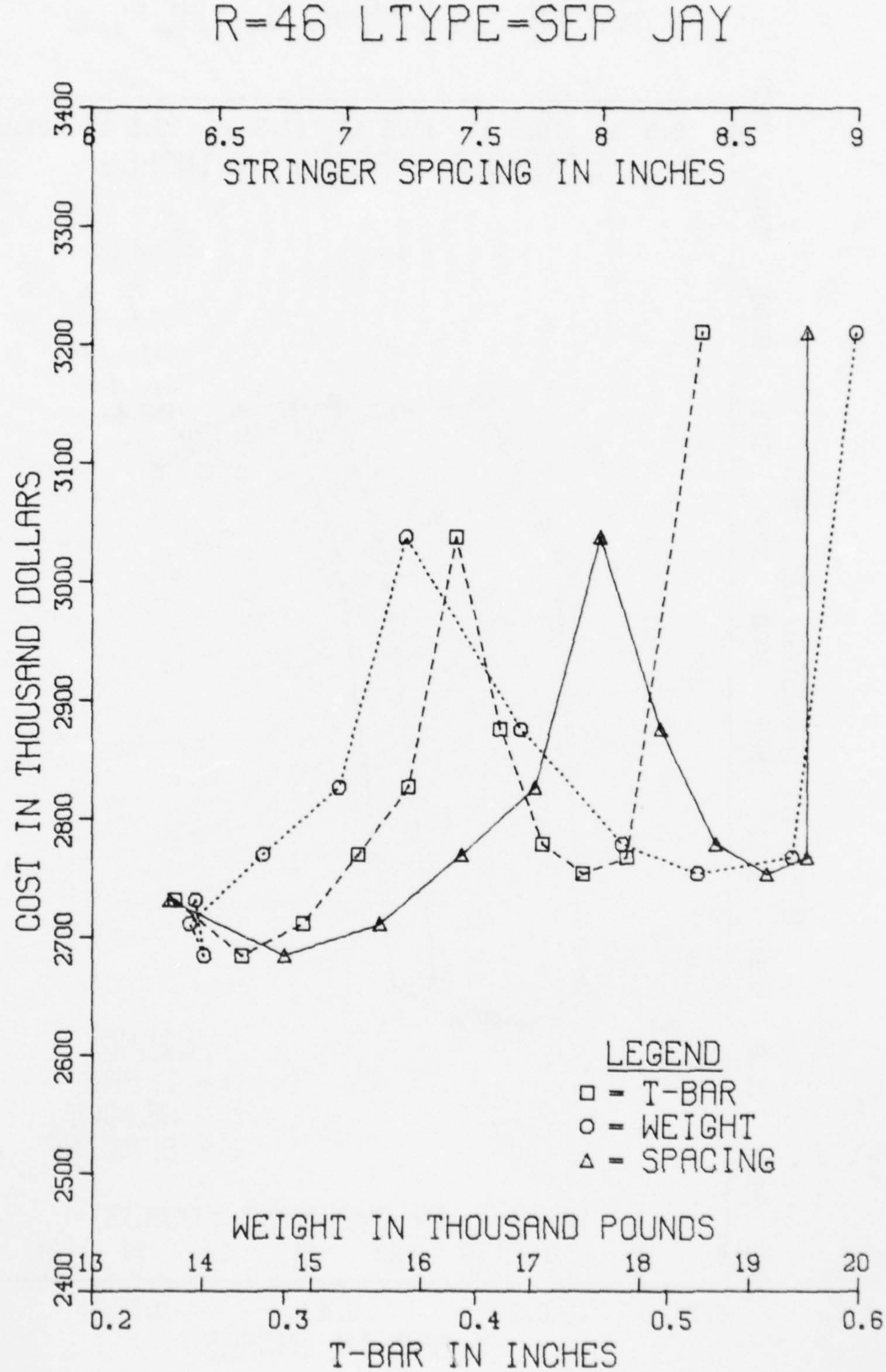
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7.5
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9
COST IN THOUSAND DOLLARS
2400
2500
2600
2700
2800
2900
3000
3100
3200
3300
3400
LEGEND
□ = T-BAR
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△ = SPACING
WEIGHT IN THOUSAND POUNDS
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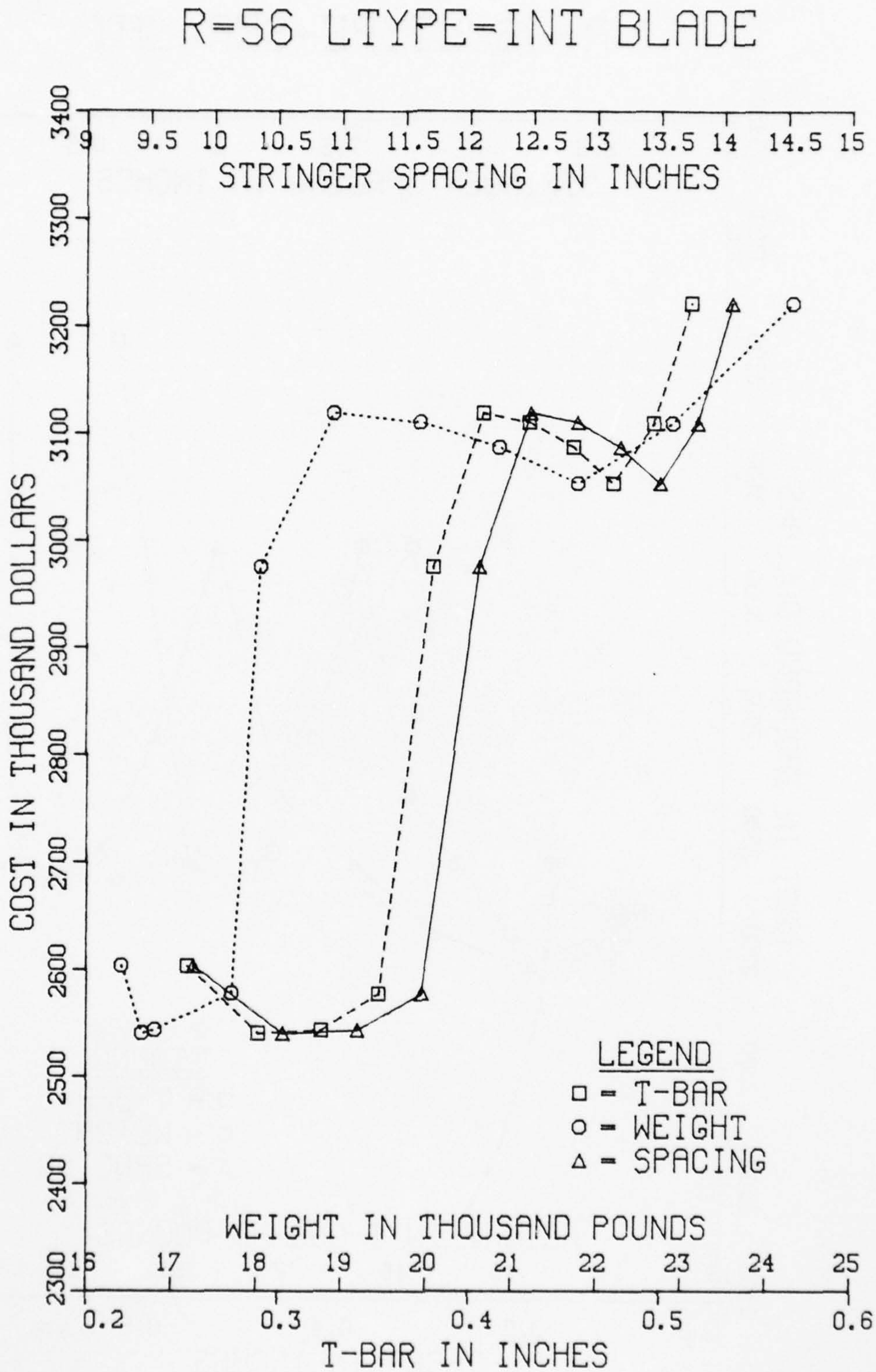
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13.5
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14.5
15
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COST IN THOUSAND DOLLARS
3400
3300
3200
3100
3000
2900
2800
2700
2600
2500
2400
2300
LEGEND
□ = T-BAR
○ = WEIGHT
△ = SPACING
WEIGHT IN THOUSAND POUNDS
16
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18
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0.4
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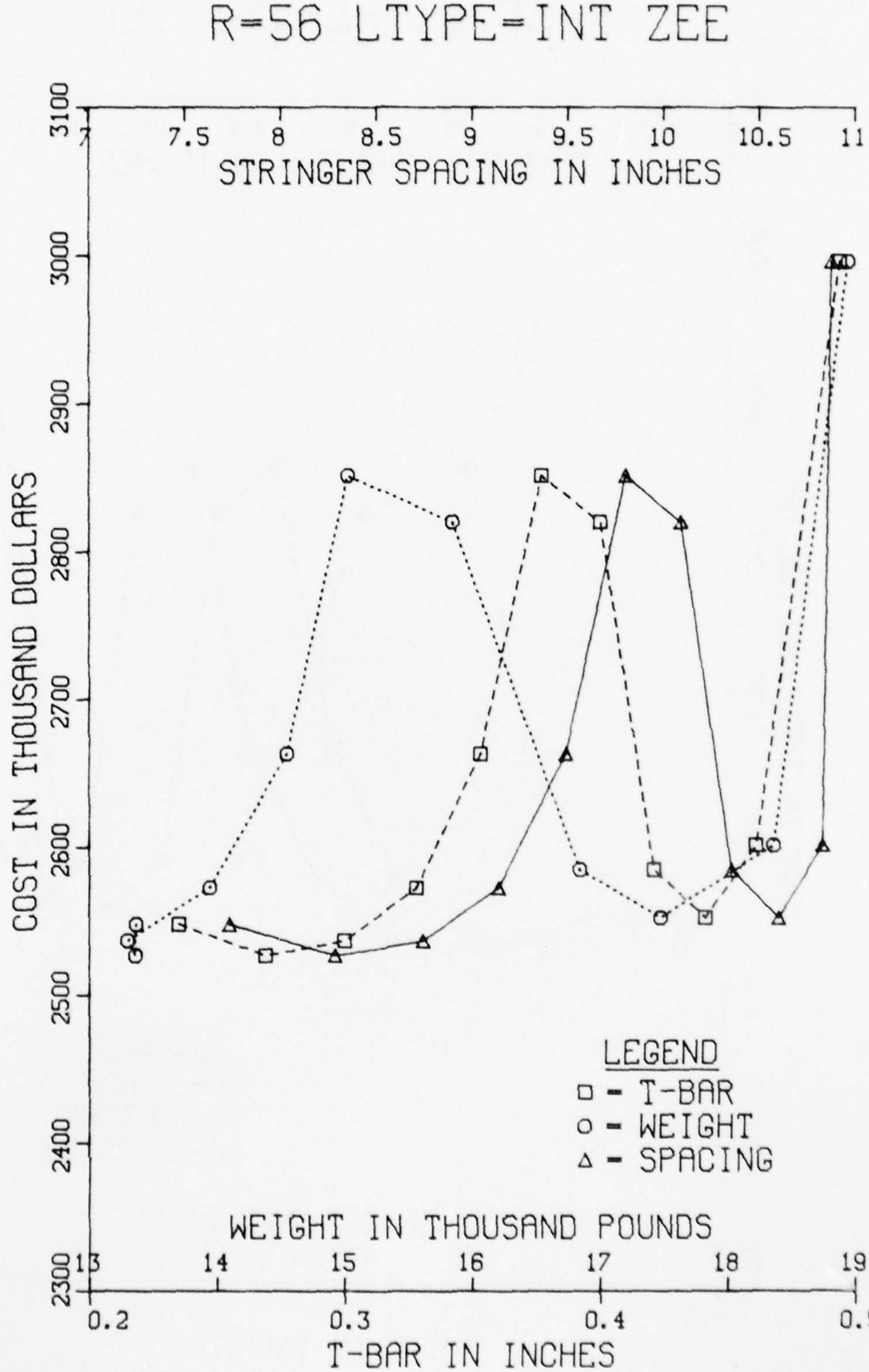
0.6
T-BAR IN INCHES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10.5
11
STRINGER SPACING IN INCHES
3100
3000
2900
2800
2700
2600
2500
2400
2300
COST IN THOUSAND DOLLARS
LEGEND
□ - T-BAR
○ - WEIGHT
△ - SPACING
WEIGHT IN THOUSAND POUNDS
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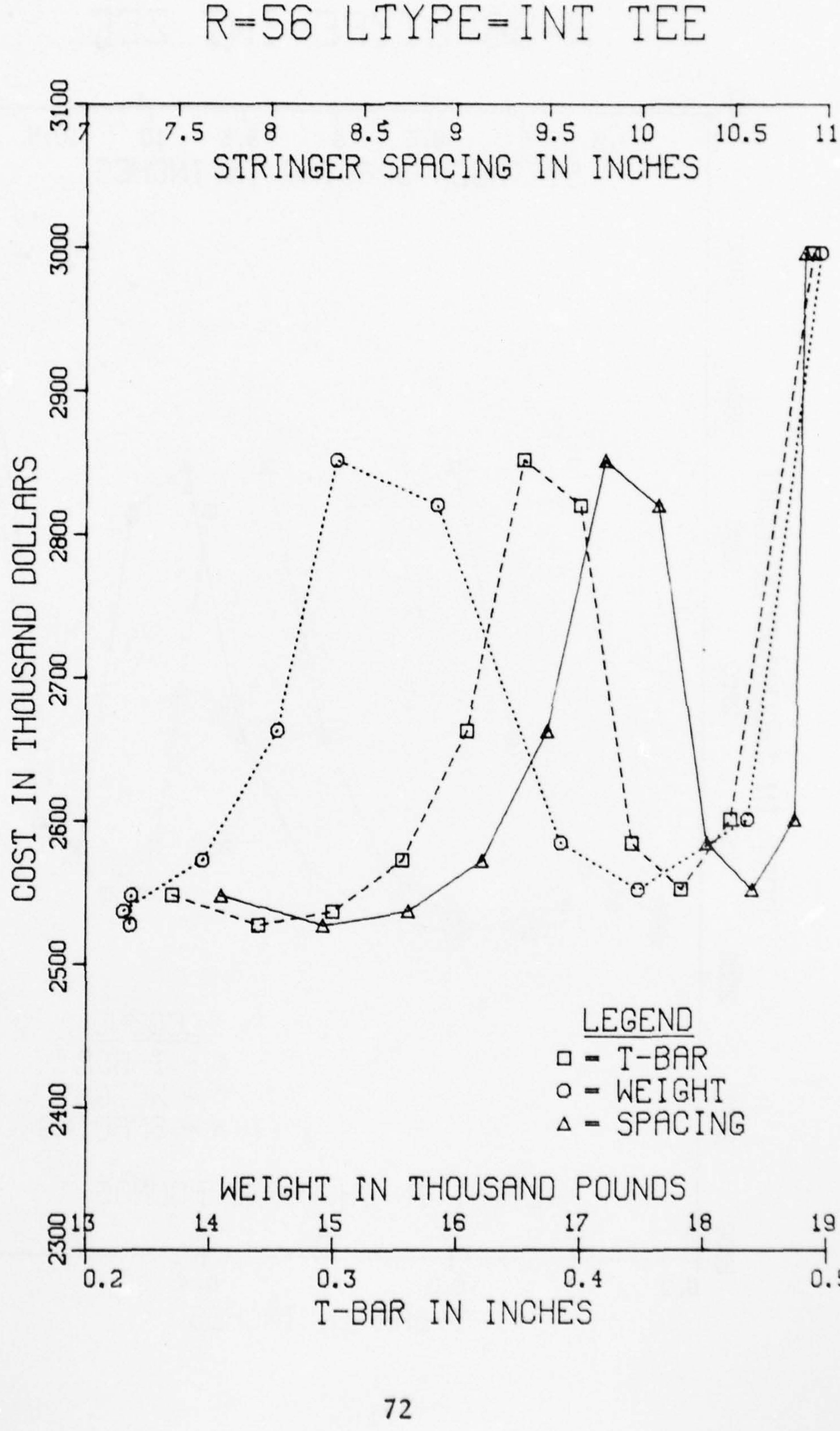
14
15
16
17
18
19
0.2
0.3
0.4
0.5
T-BAR IN INCHES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10.5
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COST IN THOUSAND DOLLARS
2300
2400
2500
2600
2700
2800
2900
3000
3100
LEGEND
□ = T-BAR
○ = WEIGHT
△ = SPACING
WEIGHT IN THOUSAND POUNDS
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14
15
16
17
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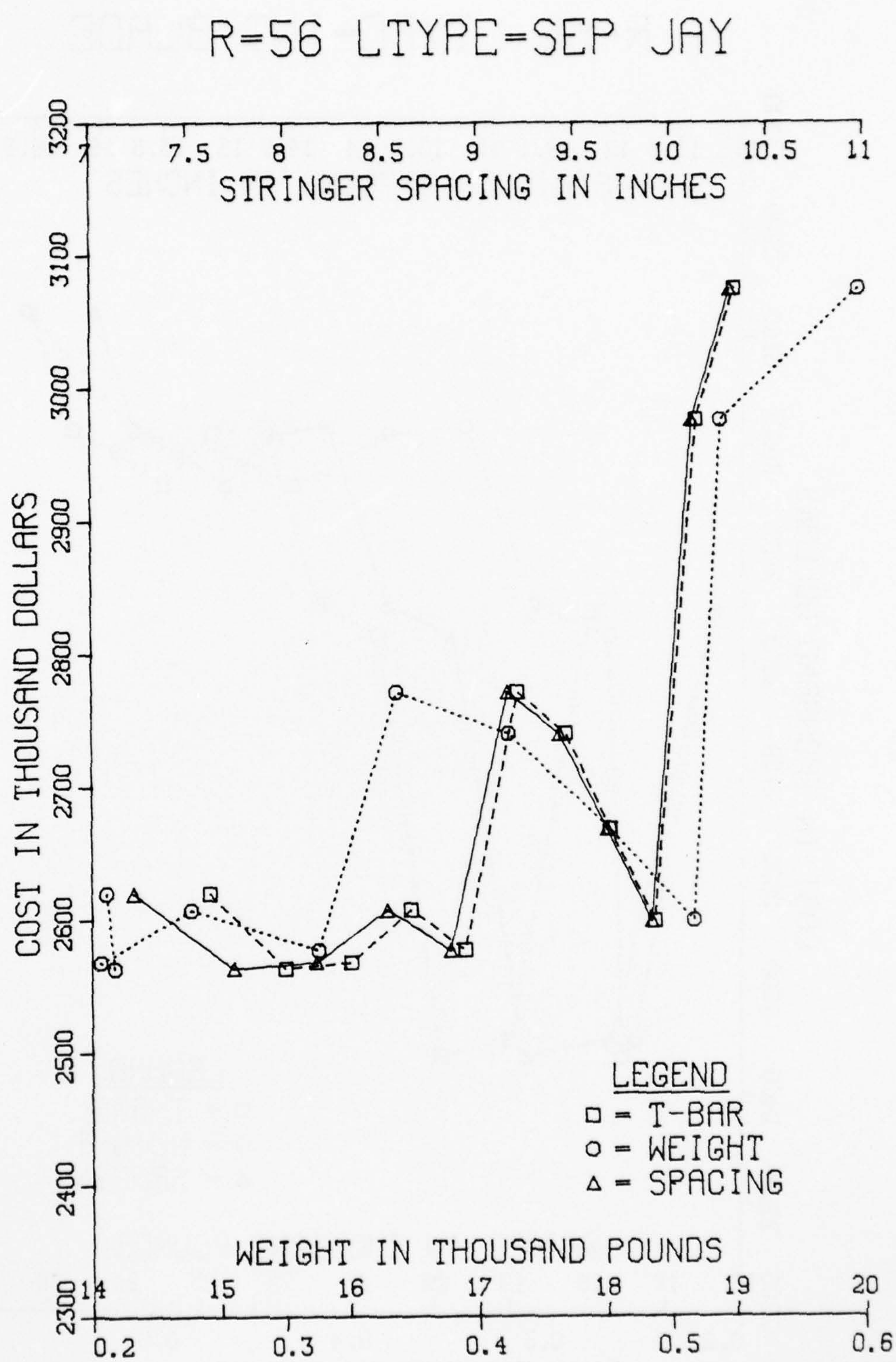
0.3
0.4
0.5
T-BAR IN INCHES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COST IN THOUSAND DOLLARS
3200
3100
3000
2900
2800
2700
2600
2500
2400
2300
LEGEND
□ = T-BAR
○ = WEIGHT
△ = SPACING
WEIGHT IN THOUSAND POUNDS
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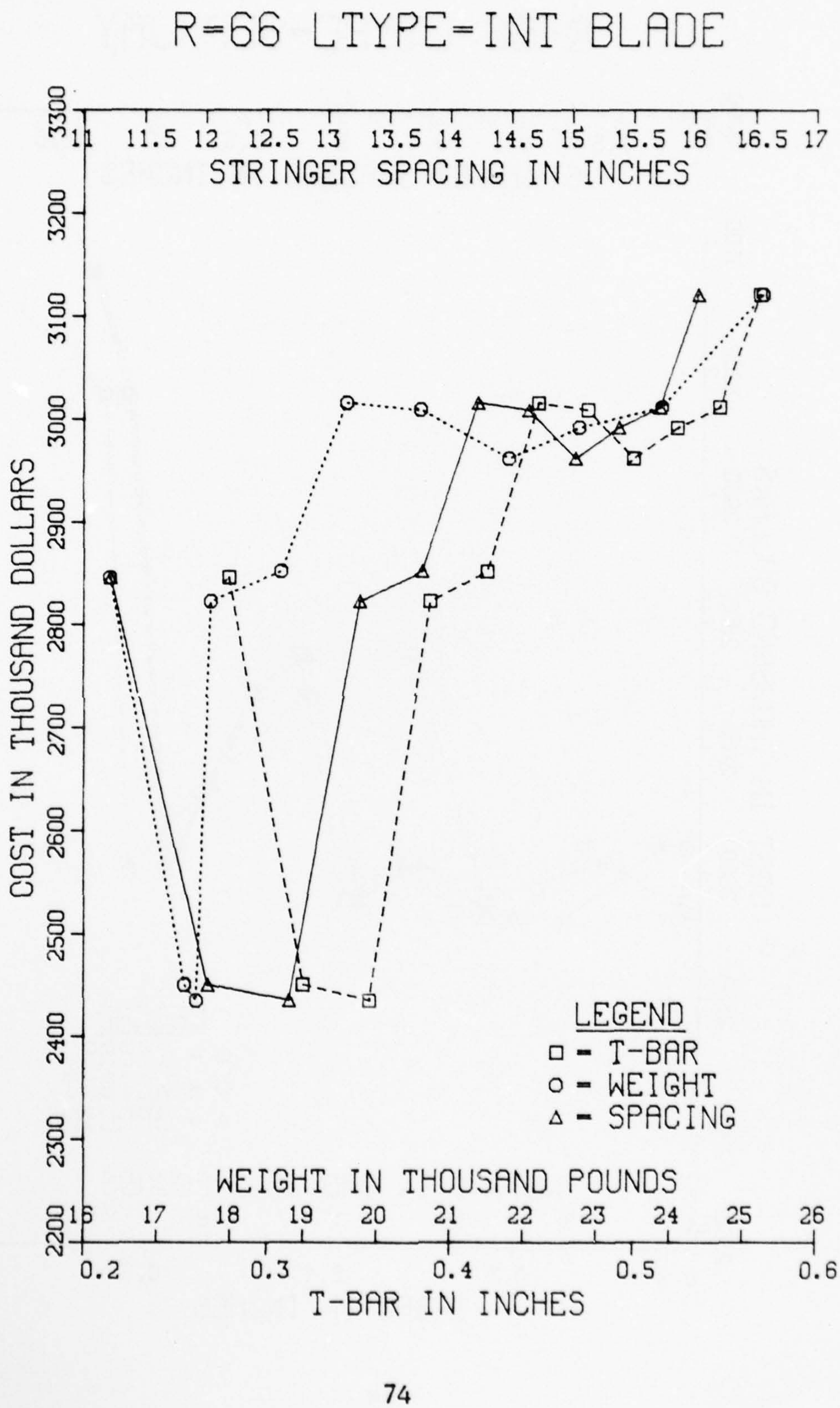
15
16
17
18
19
20
0.2
0.3
0.4
0.5
0.6
T-BAR IN INCHES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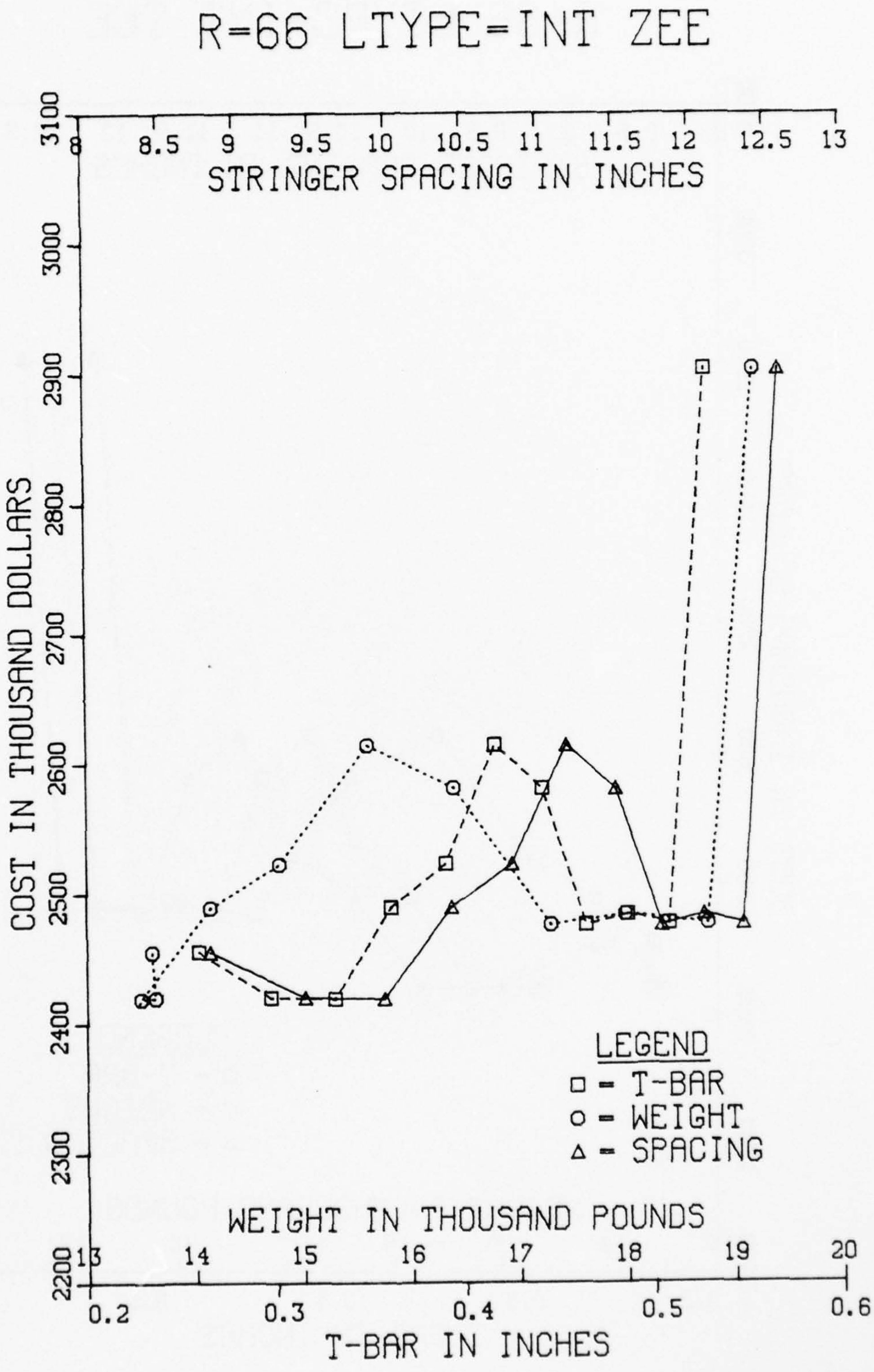
COST IN THOUSAND DOLLARS
3300 3200 3100 3000 2900 2800 2700 2600 2500 2400 2300 2200
LEGEND
□ - T-BAR
○ - WEIGHT
△ - SPACING
WEIGHT IN THOUSAND POUNDS
16 17 18 19 20 21 22 23 24 25 26
0.2 0.3 0.4 0.5 0.6
T-BAR IN INCHES



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8
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11
11.5
12
12.5
13
COST IN THOUSAND DOLLARS
3100
3000
2900
2800
2700
2600
2500
2400
2300
2200
LEGEND
□ = T-BAR
○ = WEIGHT
△ = SPACING
WEIGHT IN THOUSAND POUNDS
13
14
15
16
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20
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0.3
0.4
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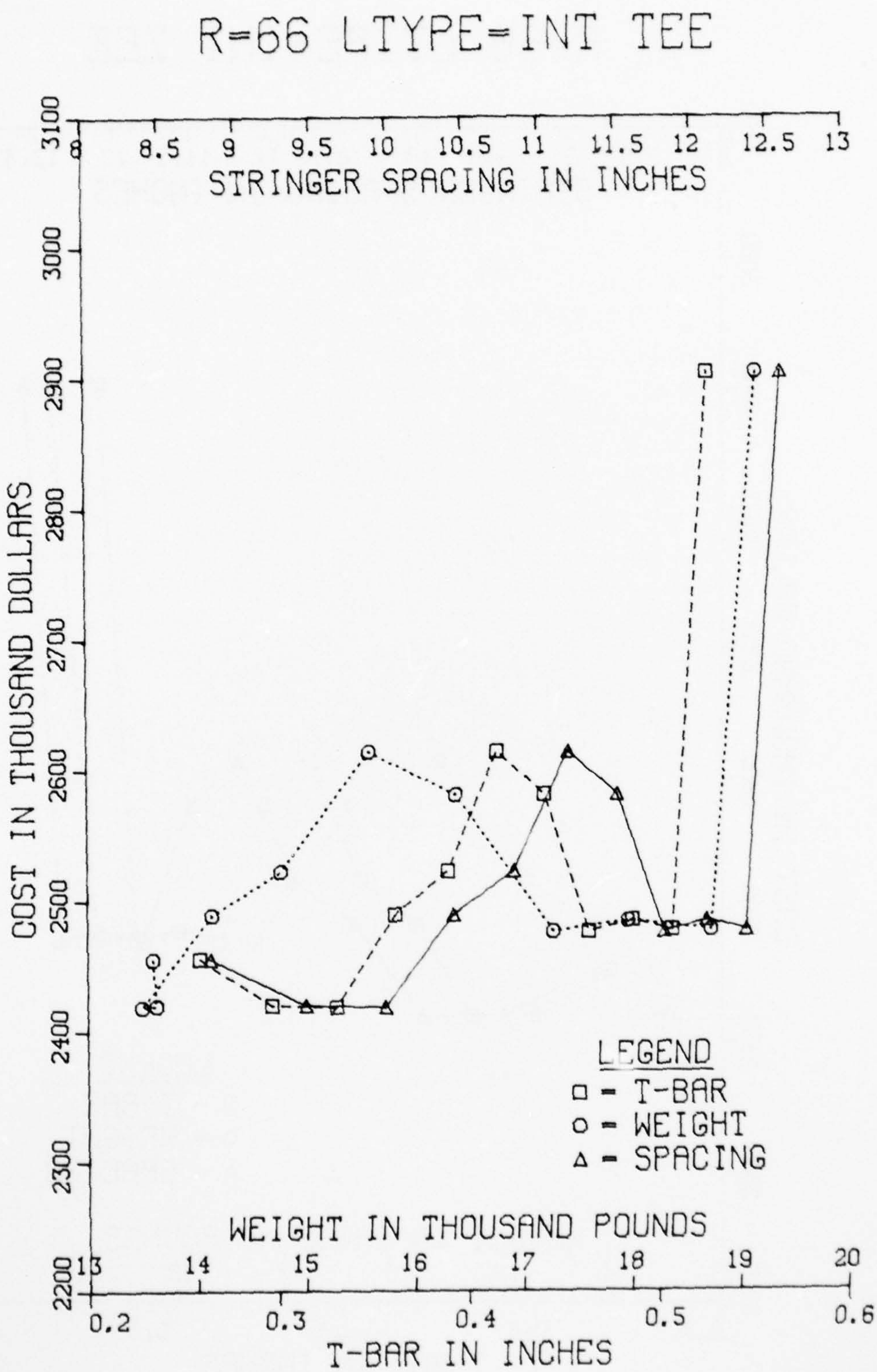
0.6
T-BAR IN INCHES



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LEGEND
□ = T-BAR
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WEIGHT IN THOUSAND POUNDS
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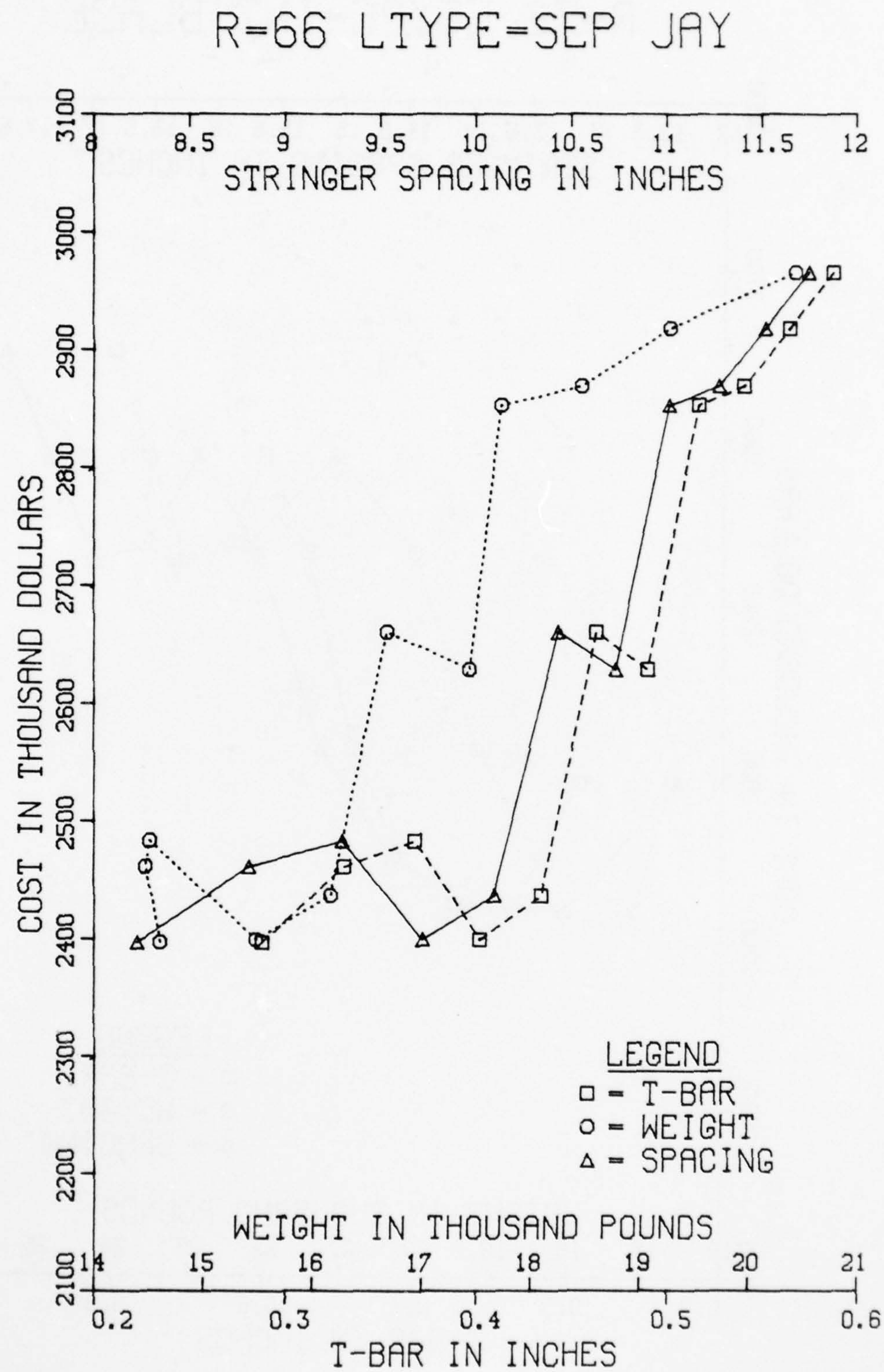
T-BAR IN INCHES



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STRINGER SPACING IN INCHES
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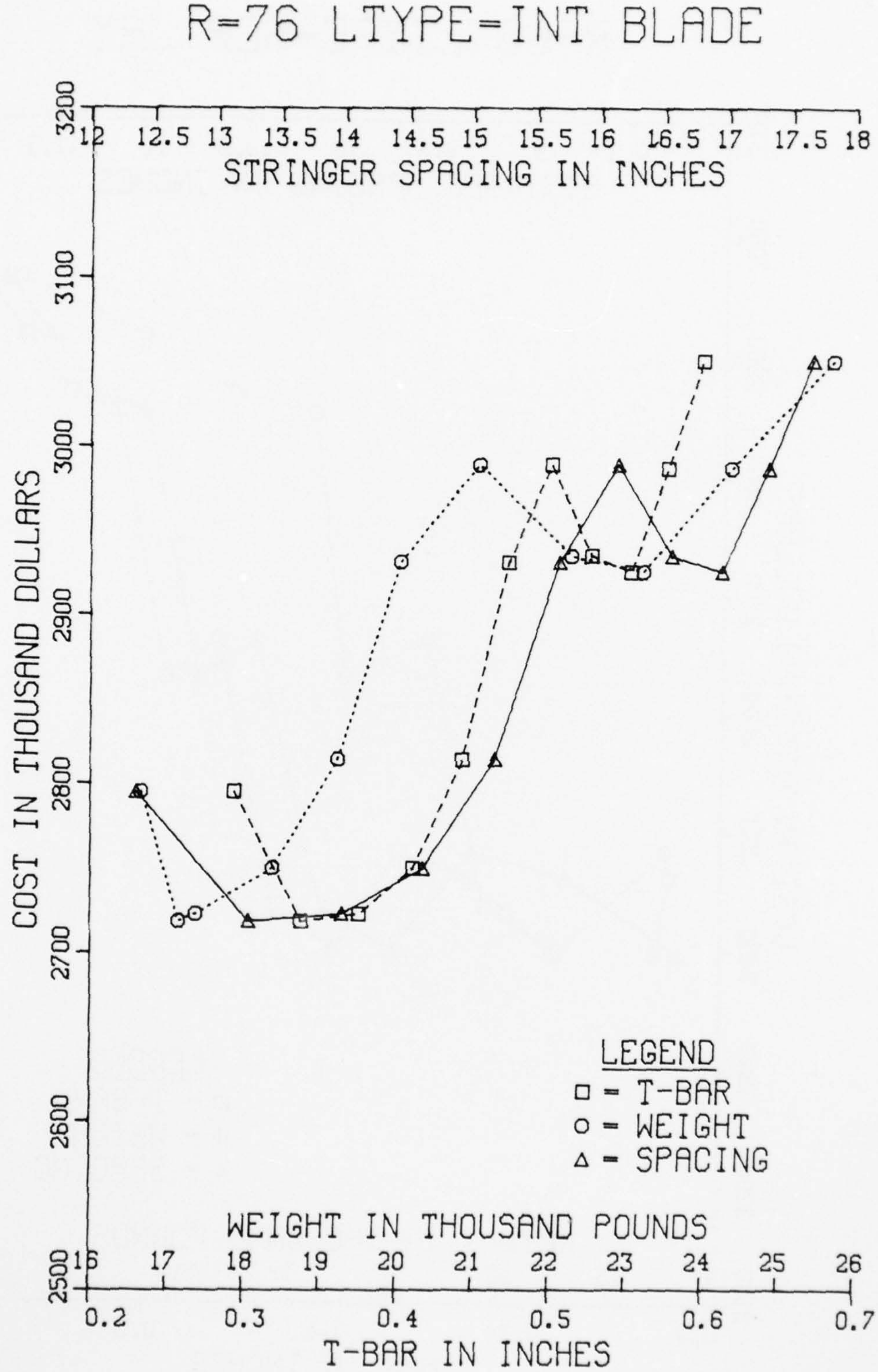
10
10.5
11
11.5
12
COST IN THOUSAND DOLLARS
3100
3000
2900
2800
2700
2600
2500
2400
2300
2200
2100
LEGEND
□ = T-BAR
○ = WEIGHT
△ = SPACING
WEIGHT IN THOUSAND POUNDS
14
15
16
17
18
19
20
21
0.2
0.3
0.4
0.5
0.6
T-BAR IN INCHES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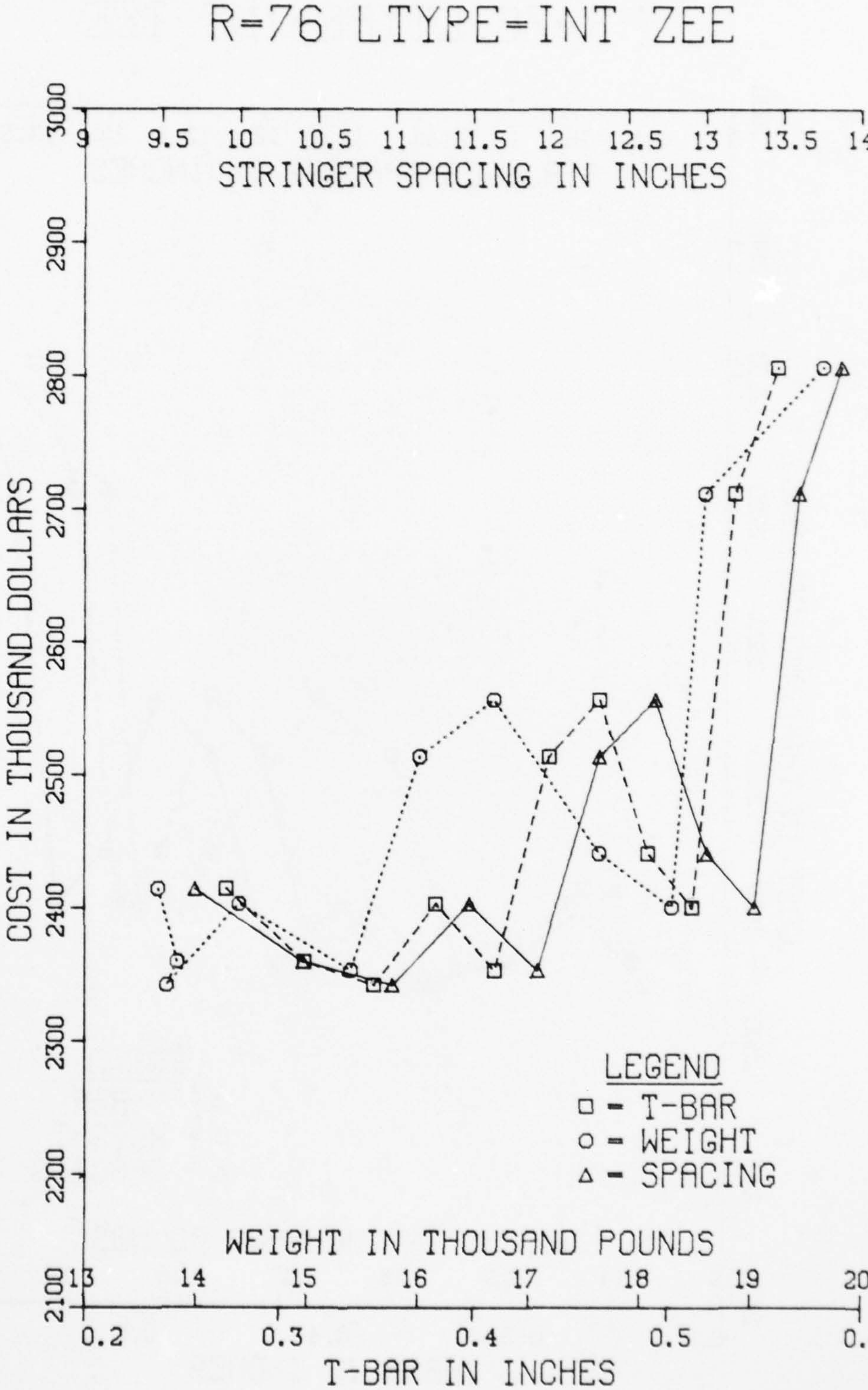
12.5
13
13.5
14
14.5
15
15.5
16
16.5
17
17.5
18
STRINGER SPACING IN INCHES
3200
3100
3000
2900
2800
2700
2600
2500
COST IN THOUSAND DOLLARS
LEGEND
□ = T-BAR
○ = WEIGHT
△ = SPACING
WEIGHT IN THOUSAND POUNDS
16
17
18
19
20
21
22
23
24
25
26
0.2
0.3
0.4
0.5
0.6
0.7
T-BAR IN INCHES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COST IN THOUSAND DOLLARS
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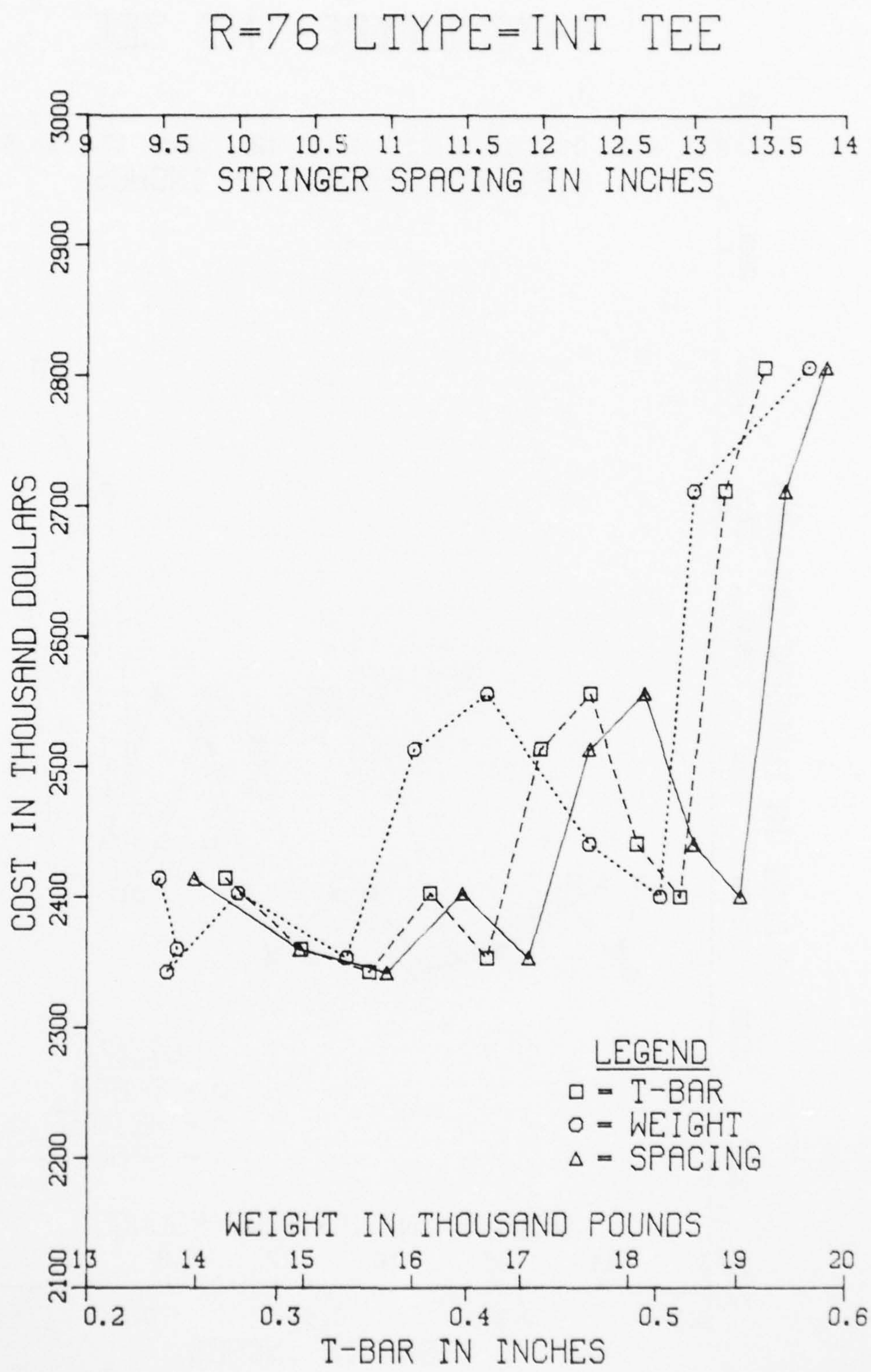
LEGEND
□ - T-BAR
○ - WEIGHT
△ - SPACING
WEIGHT IN THOUSAND POUNDS
13 14 15 16 17 18 19 20
0.2 0.3 0.4 0.5 0.6
T-BAR IN INCHES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COST IN THOUSAND DOLLARS
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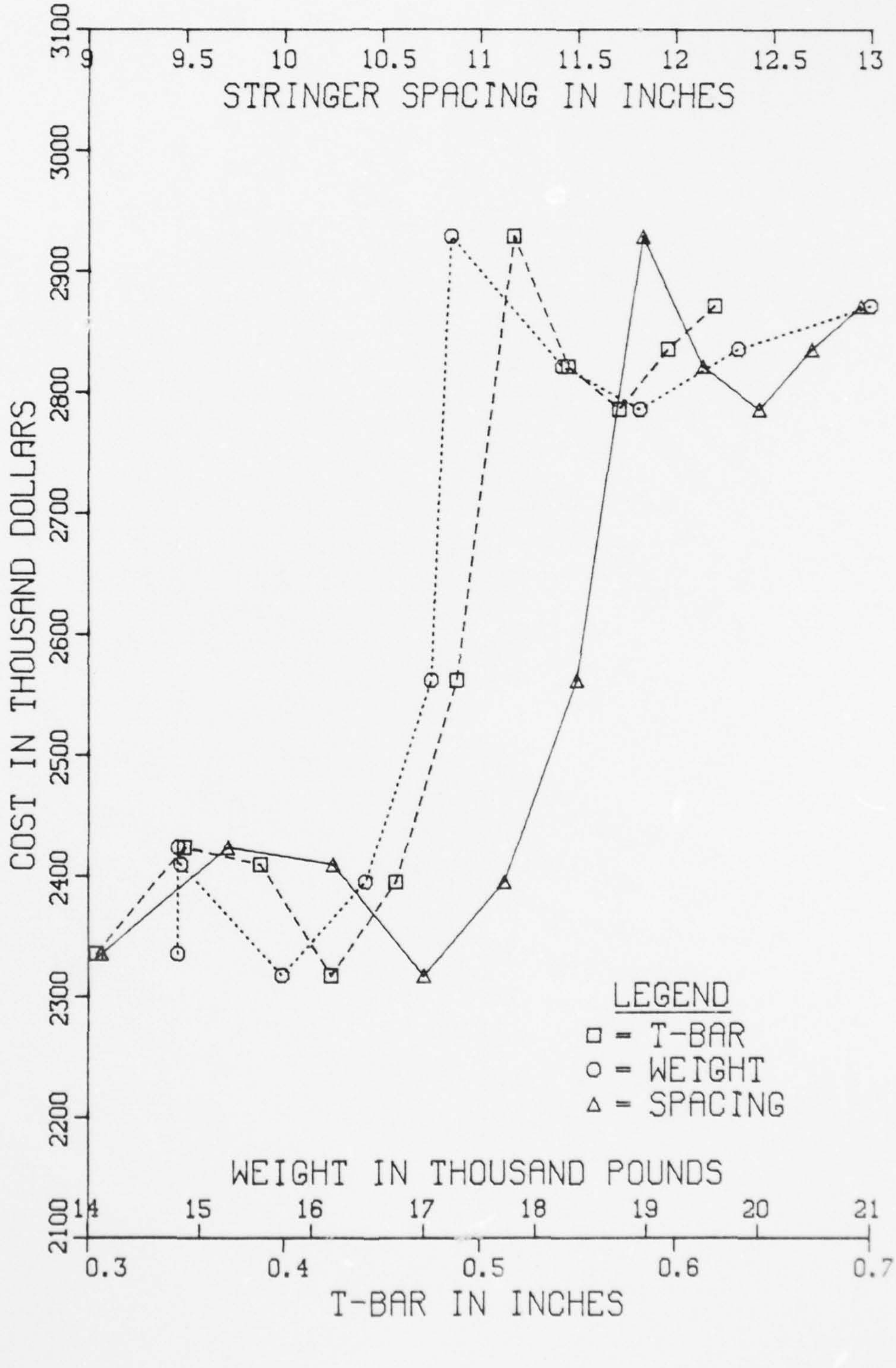
LEGEND
□ = T-BAR
○ = WEIGHT
△ = SPACING
WEIGHT IN THOUSAND POUNDS
13 14 15 16 17 18 19 20
0.2 0.3 0.4 0.5 0.6
T-BAR IN INCHES

R=76 LTYPE=SEP JAY



AD-A072 668 AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL--ETC F/G 1/3
A STUDY TO DEVELOP OPTIMIZATION ALGORITHMS FOR AIRCRAFT WING ST--ETC(U)
JUN 79 G W ABBOTT, R A MCNAMARA

UNCLASSIFIED AFIT-LSSR-23-79A NL

2 OF 2
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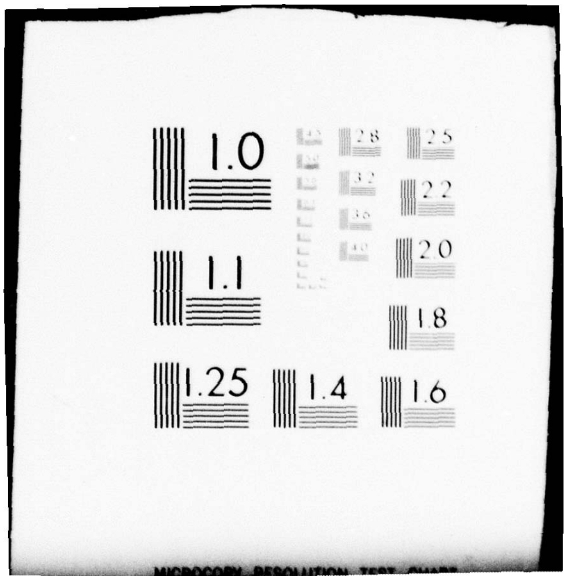


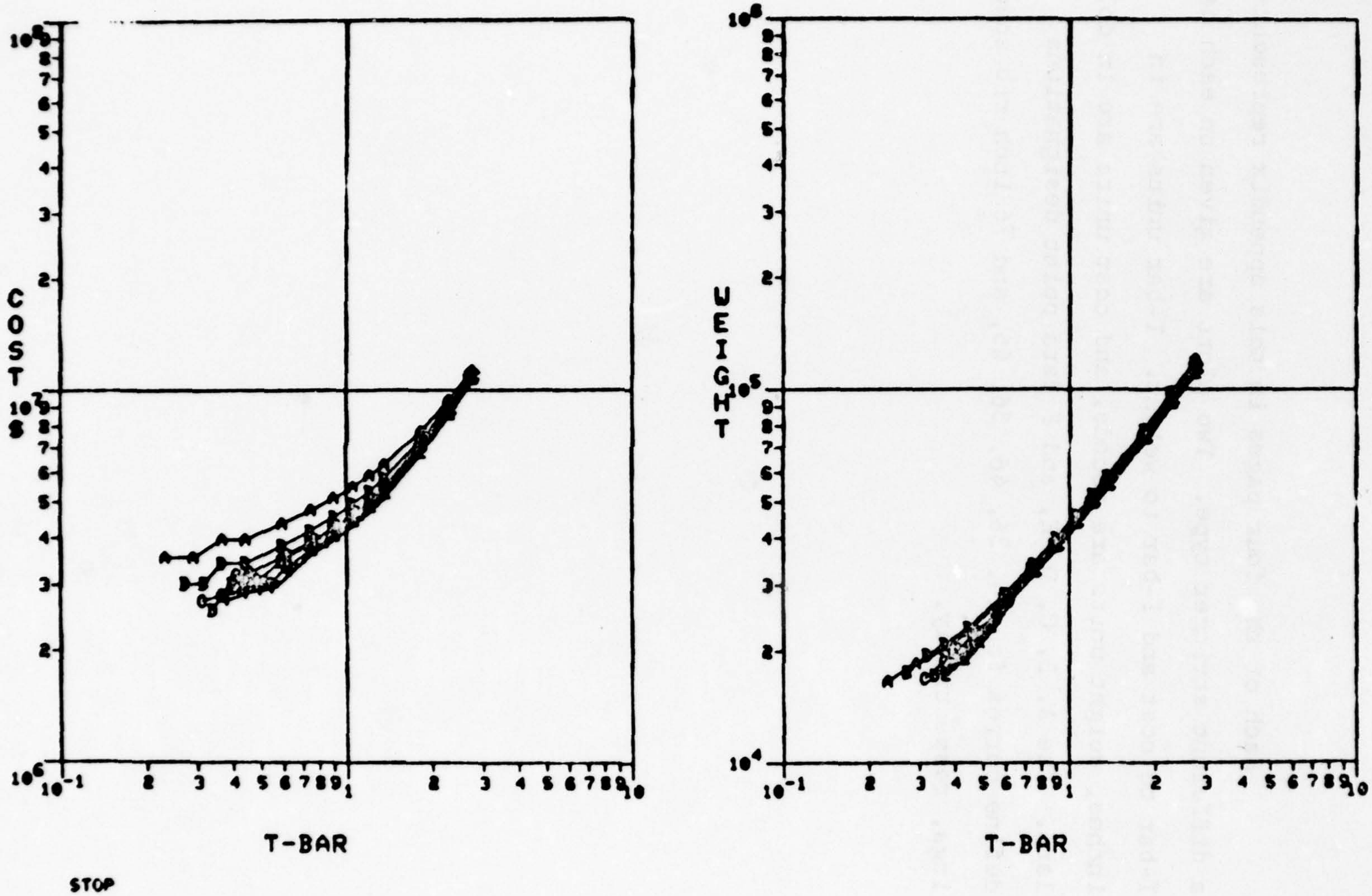
MICROCOPY RESOLUTION TEST CHART

APPENDIX E

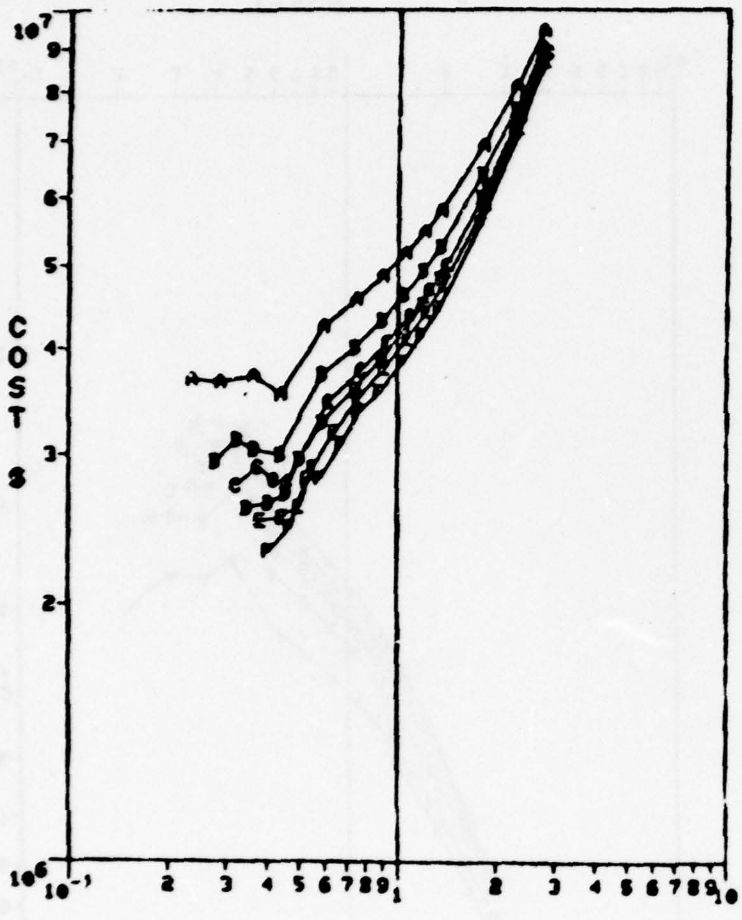
CHRISTENSEN/EVANS LOG-LOG DATA PLOTS

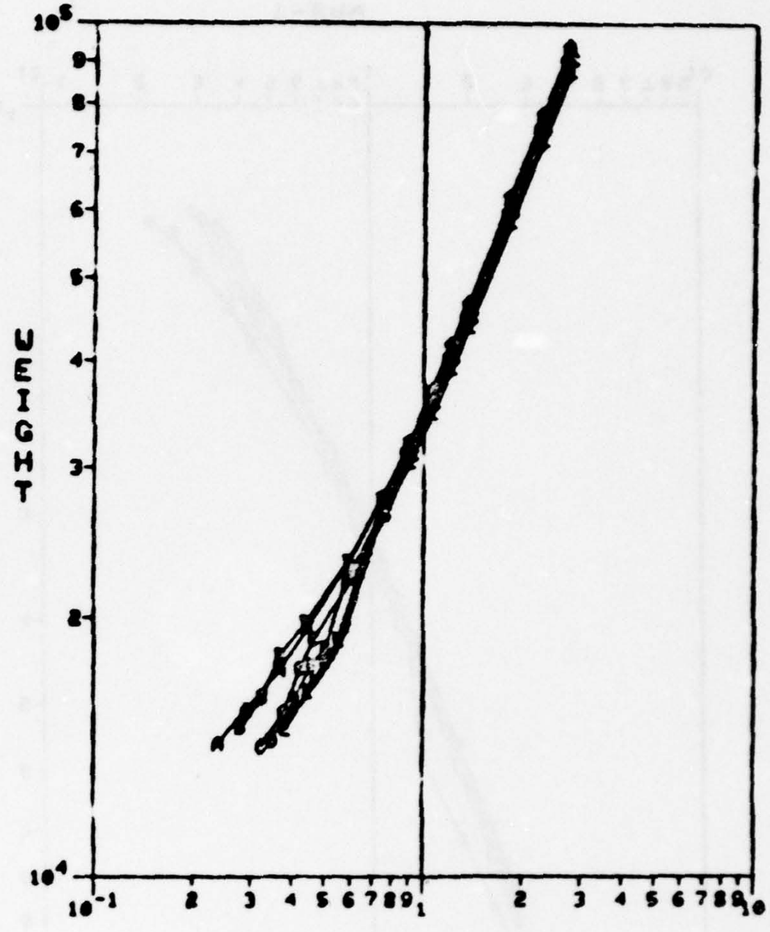
Each of the four pages in this appendix represents a different stringer type. Two plots are given on each page, T-bar to cost and T-bar to weight. T-bar units are in inches, weight units are pounds, and cost units are in dollars. The A, B, C, D, E, and F data point designations define curves for 26, 36, 46, 56, 66, and 76 inch rib spacings, respectively.

BLADE STRINGER



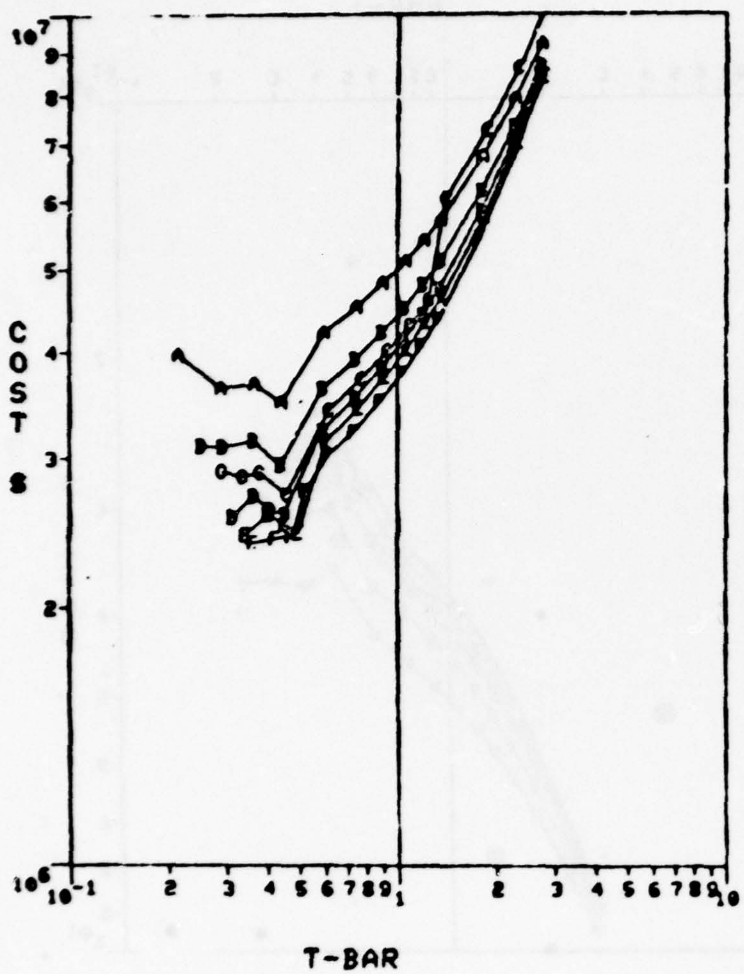
JAY STRINGER

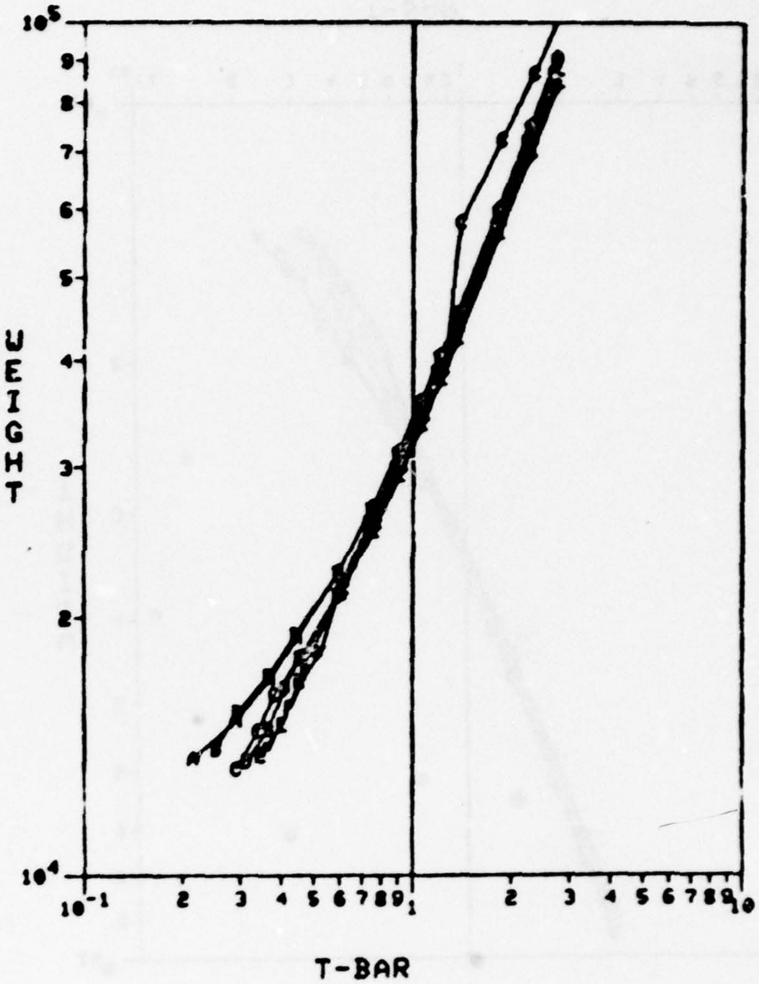




STOP

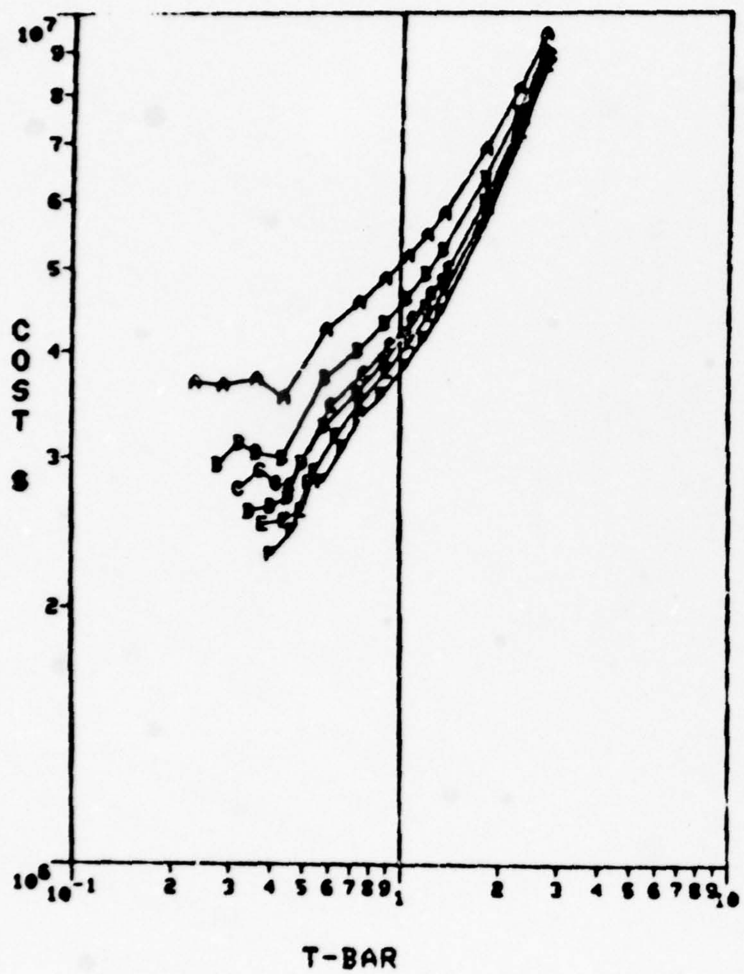
TEE STRINGER

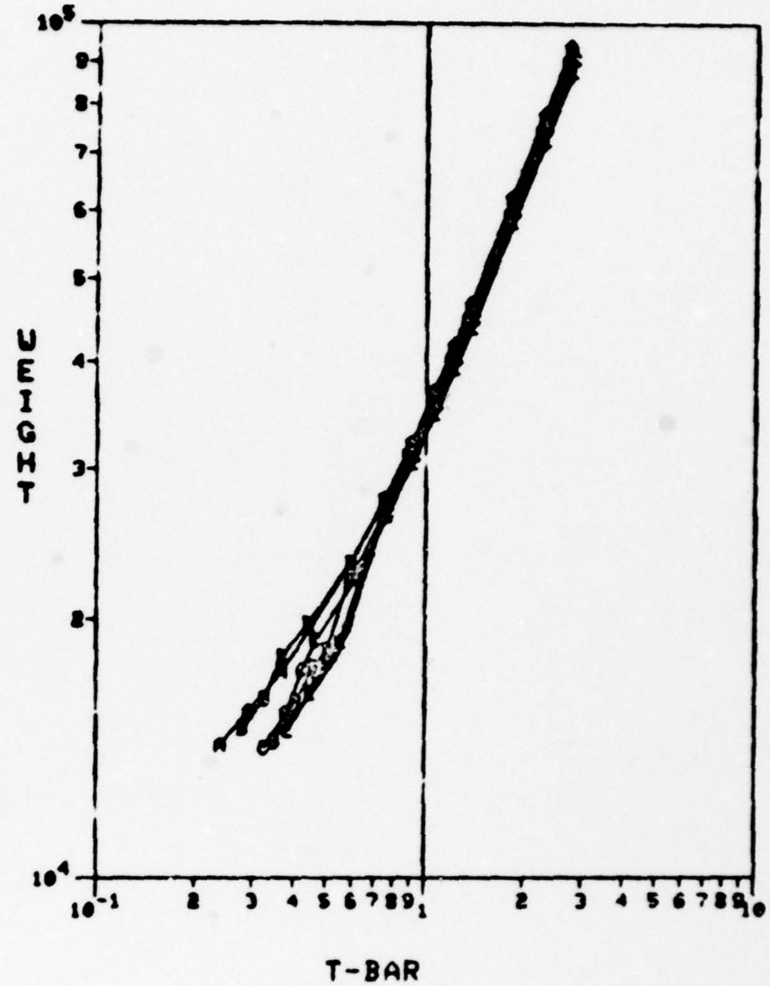




STOP

JAY STRINGER





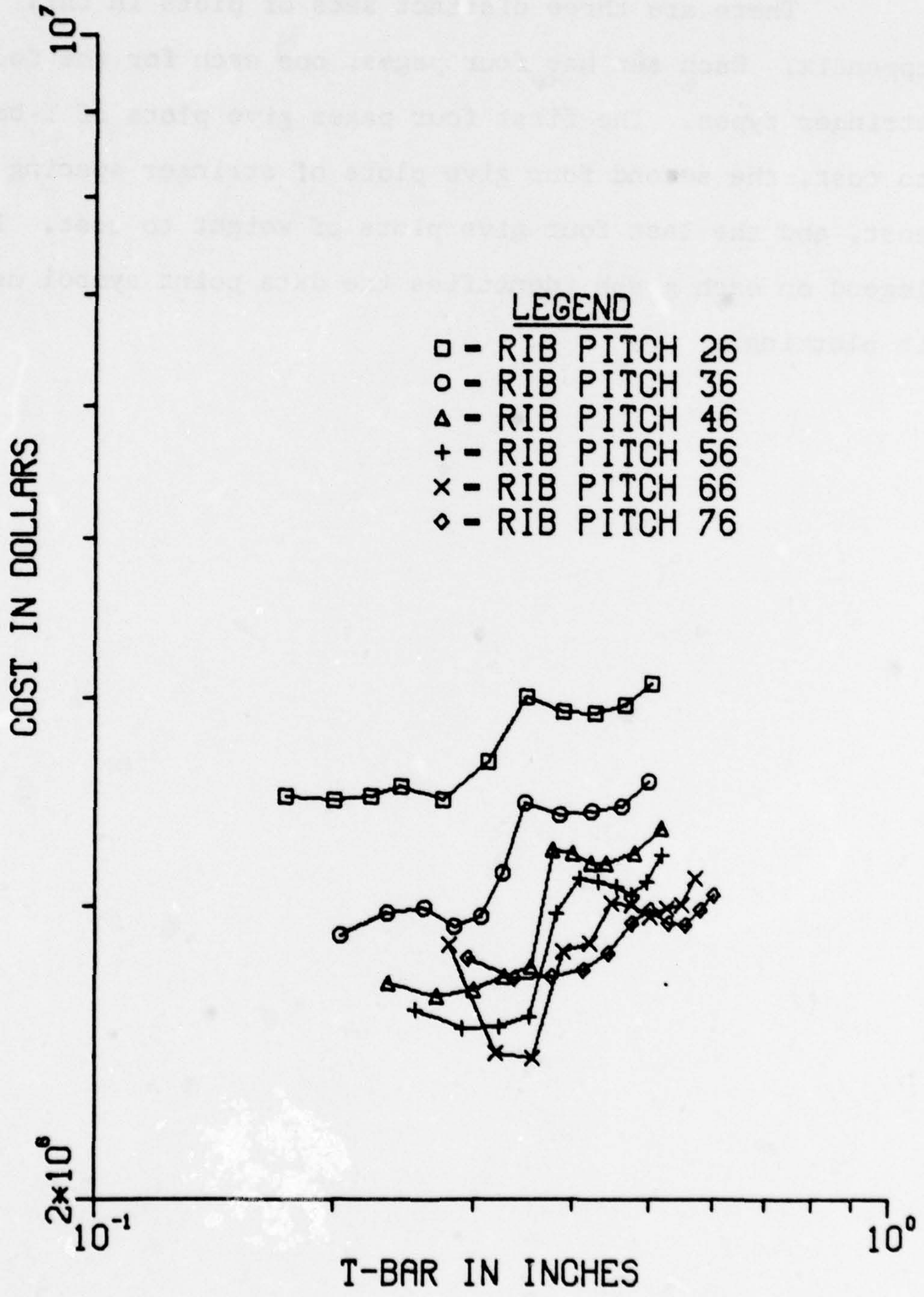
STOP

APPENDIX F

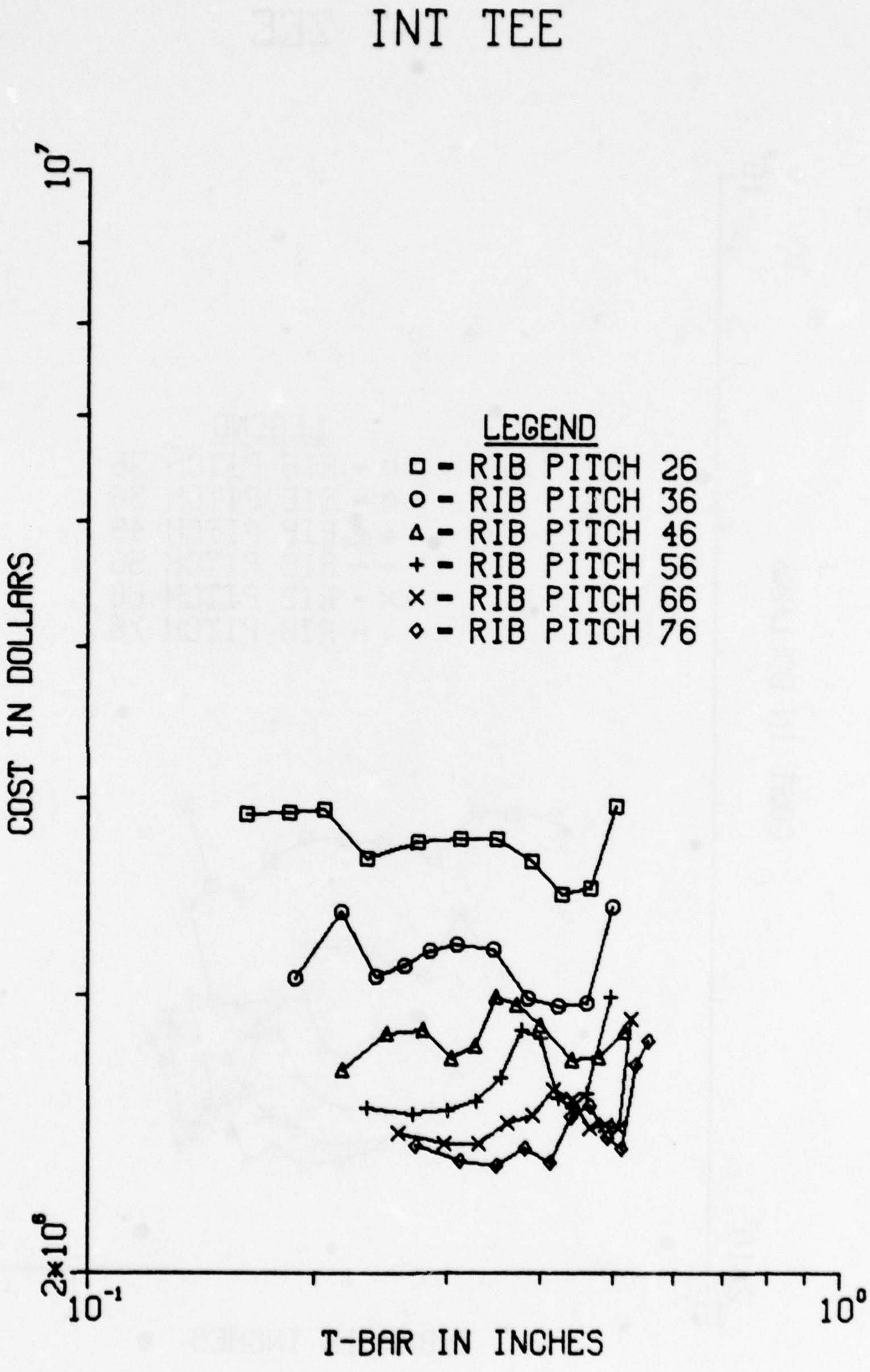
LOG-LOG DATA PLOTS

There are three distinct sets of plots in this appendix. Each set has four pages, one each for the four stringer types. The first four pages give plots of T-bar to cost, the second four give plots of stringer spacing to cost, and the last four give plots of weight to cost. The legend on each graph identifies the data point symbol used in plotting.

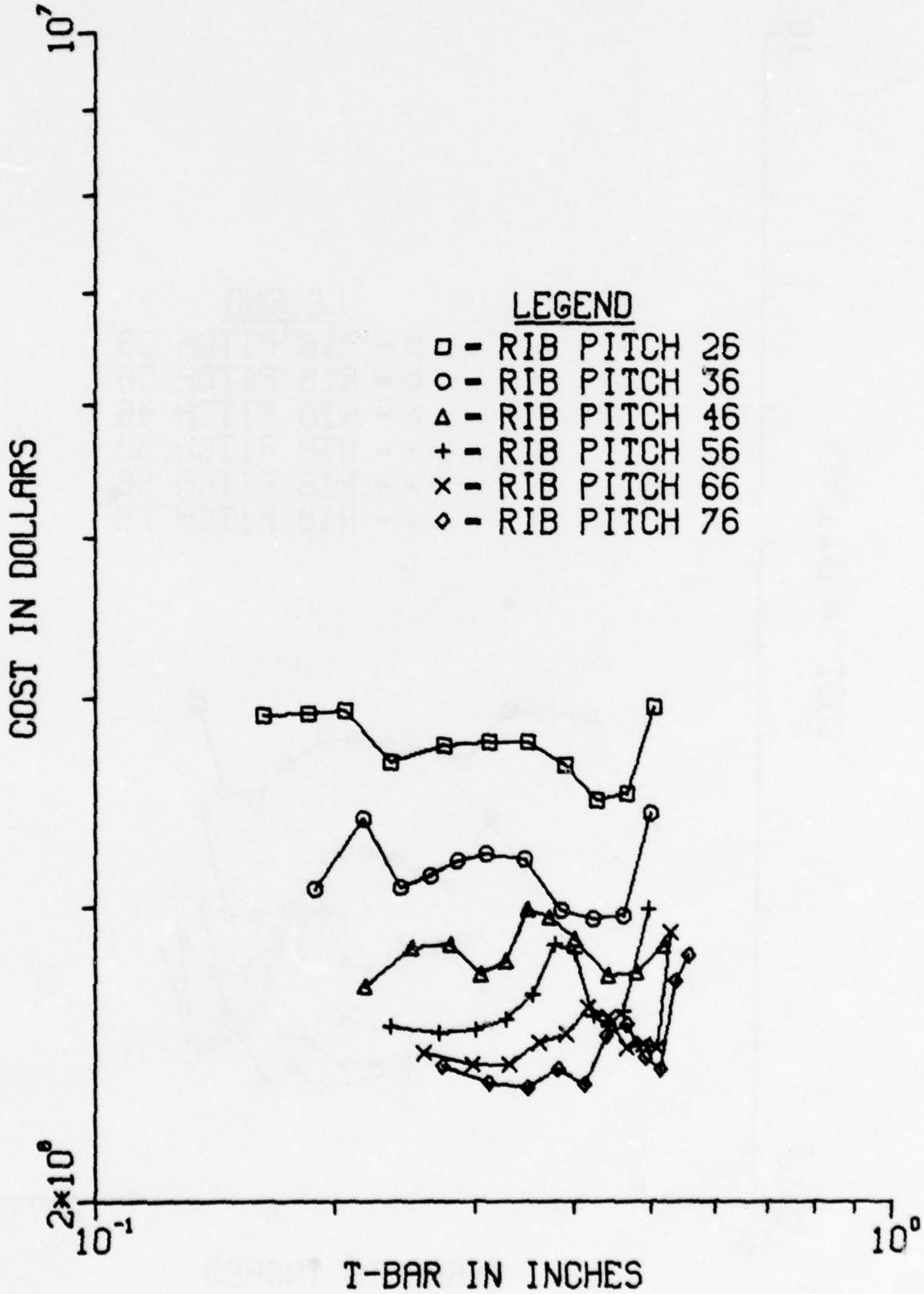
INT BLADE



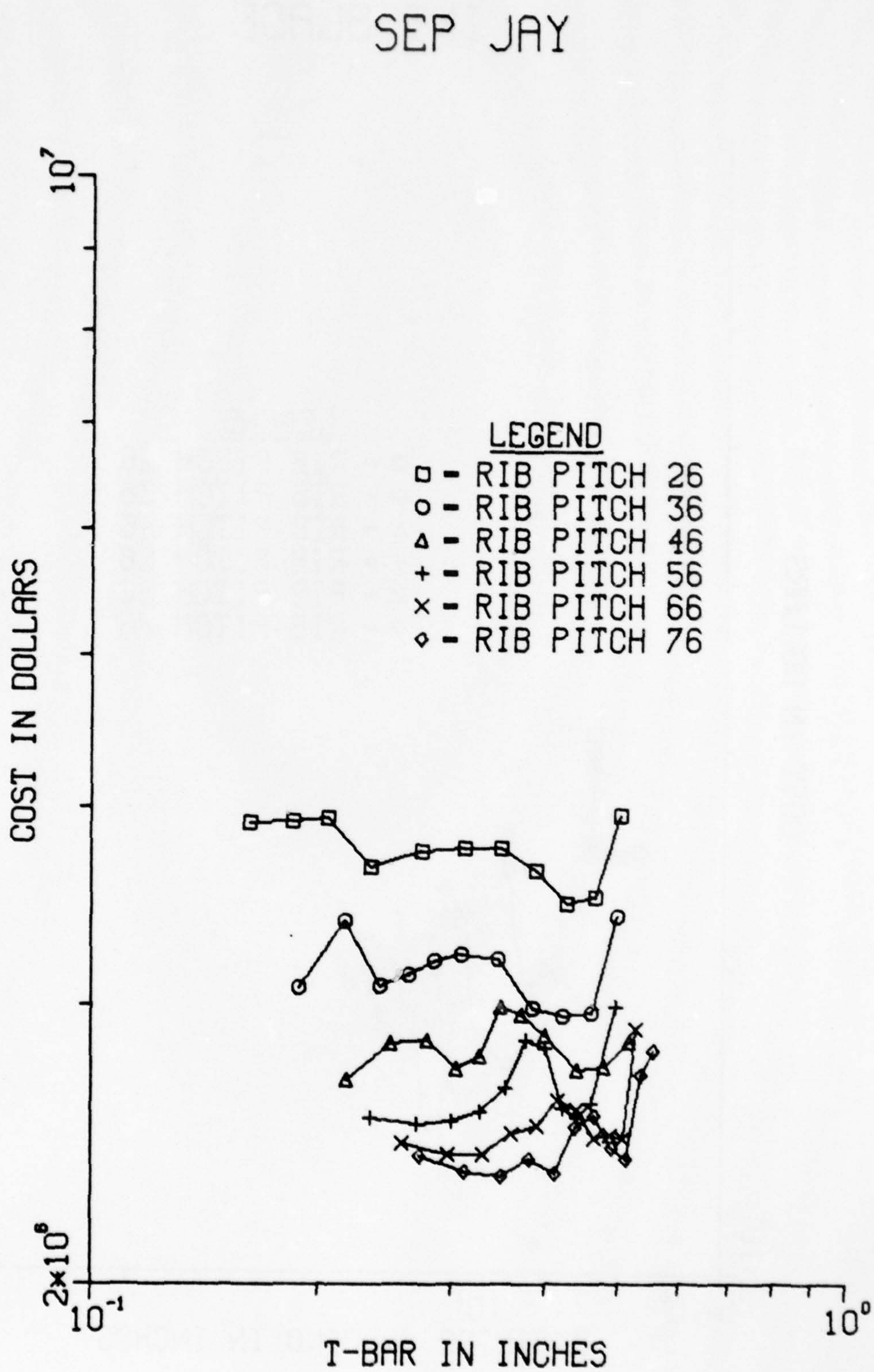
LEGEND
□ - RIB PITCH 26
○ - RIB PITCH 36
△ - RIB PITCH 46
+ - RIB PITCH 56
× - RIB PITCH 66
◇ - RIB PITCH 76
COST IN DOLLARS
10^7
2×10^6
10^{-1}
10^0
T-BAR IN INCHES

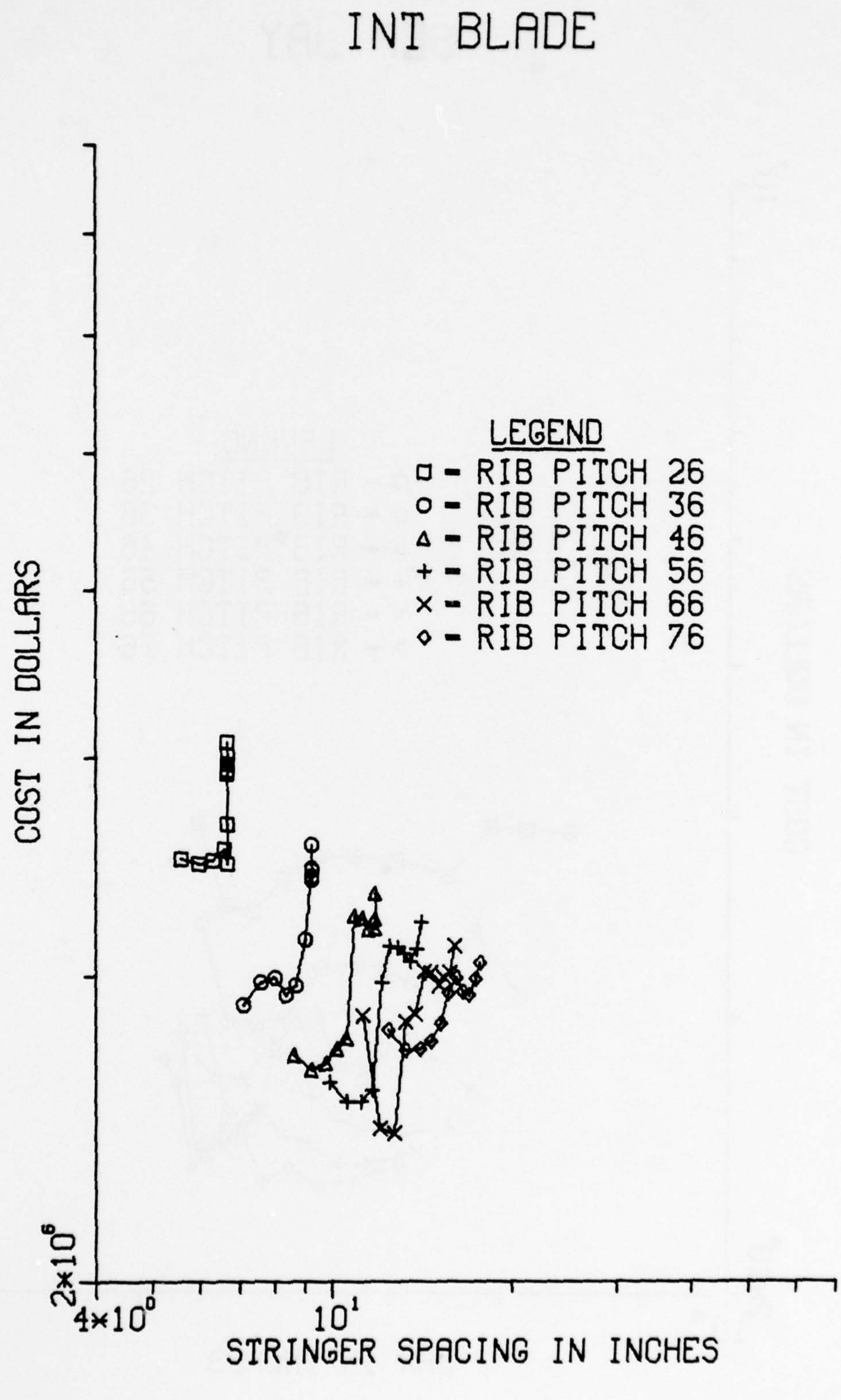

INT TEE
LEGEND
□ - RIB PITCH 26
○ - RIB PITCH 36
△ - RIB PITCH 46
+ - RIB PITCH 56
× - RIB PITCH 66
◇ - RIB PITCH 76
COST IN DOLLARS
10^7
2×10^6
10^{-1}
10^0
T-BAR IN INCHES

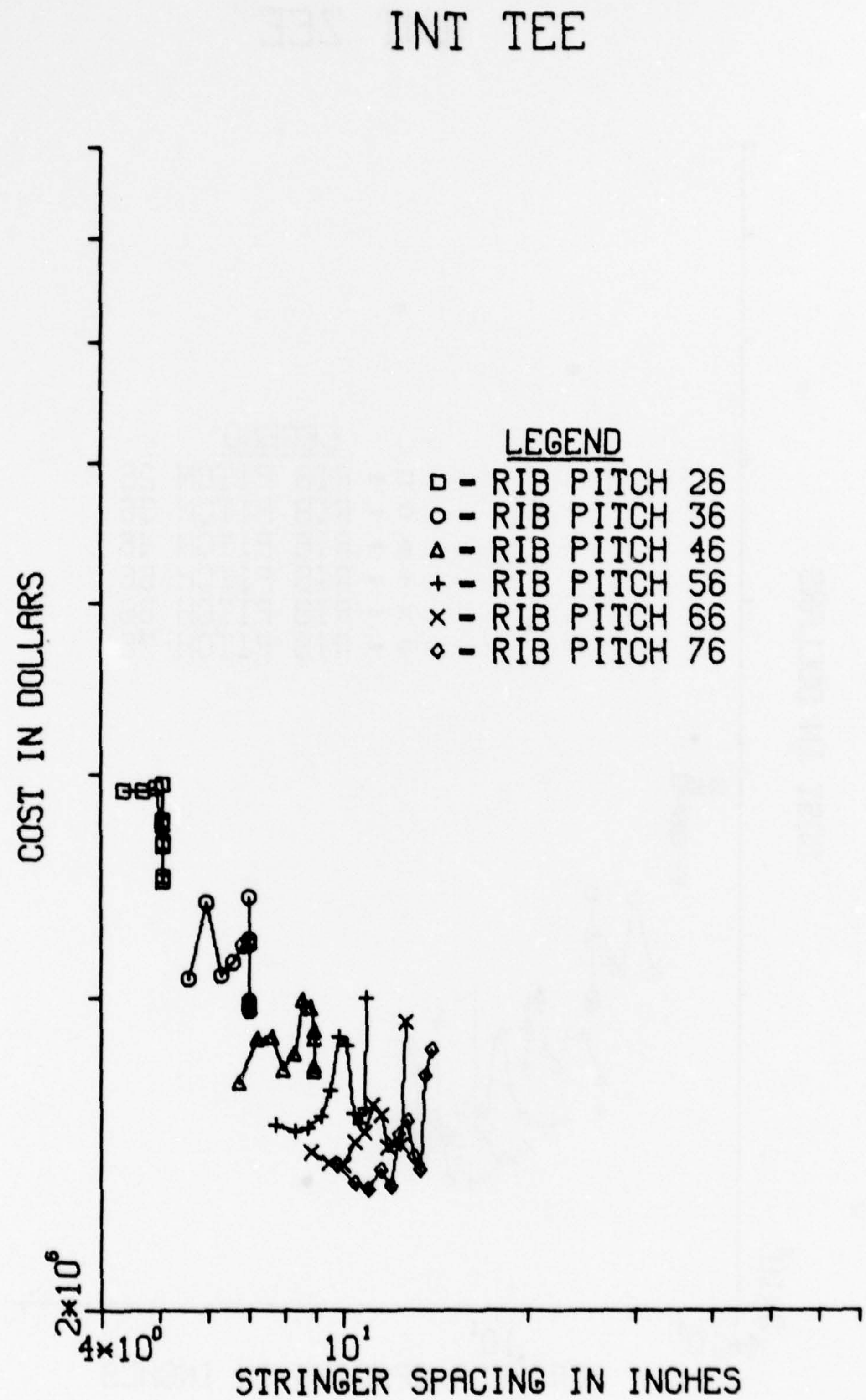
INT ZEE



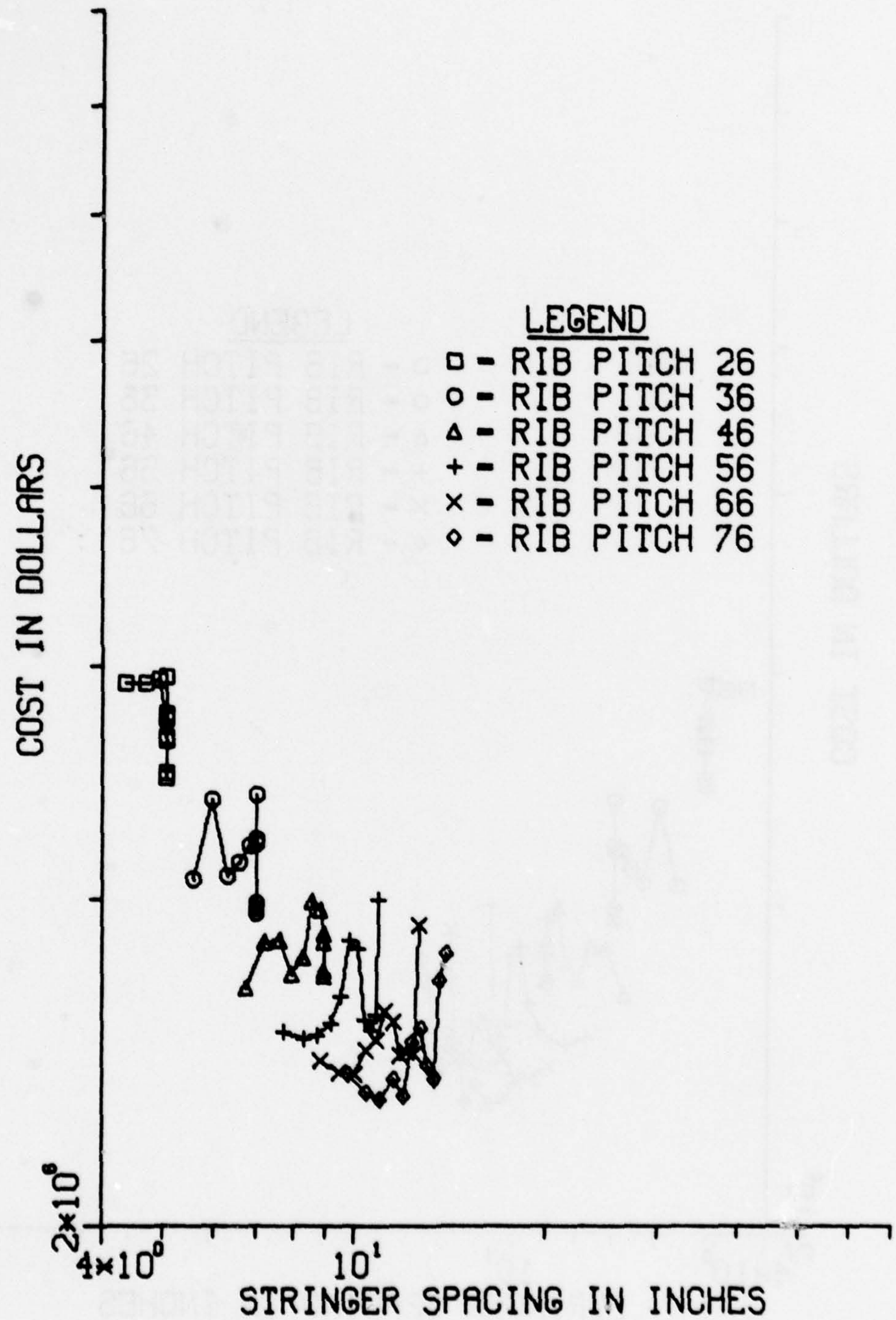
LEGEND
□ - RIB PITCH 26
○ - RIB PITCH 36
△ - RIB PITCH 46
+ - RIB PITCH 56
× - RIB PITCH 66
◇ - RIB PITCH 76
COST IN DOLLARS
10^7
$2*10^6$
10^{-1}
10^0
T-BAR IN INCHES


SEP JAY
LEGEND
□ - RIB PITCH 26
○ - RIB PITCH 36
△ - RIB PITCH 46
+ - RIB PITCH 56
× - RIB PITCH 66
◇ - RIB PITCH 76
COST IN DOLLARS
10^7
2×10^6
10^{-1}
10^0
T-BAR IN INCHES


INT BLADE
LEGEND
□ - RIB PITCH 26
○ - RIB PITCH 36
△ - RIB PITCH 46
+ - RIB PITCH 56
× - RIB PITCH 66
◇ - RIB PITCH 76
COST IN DOLLARS
2×10^6
4×10^0
10^1
STRINGER SPACING IN INCHES

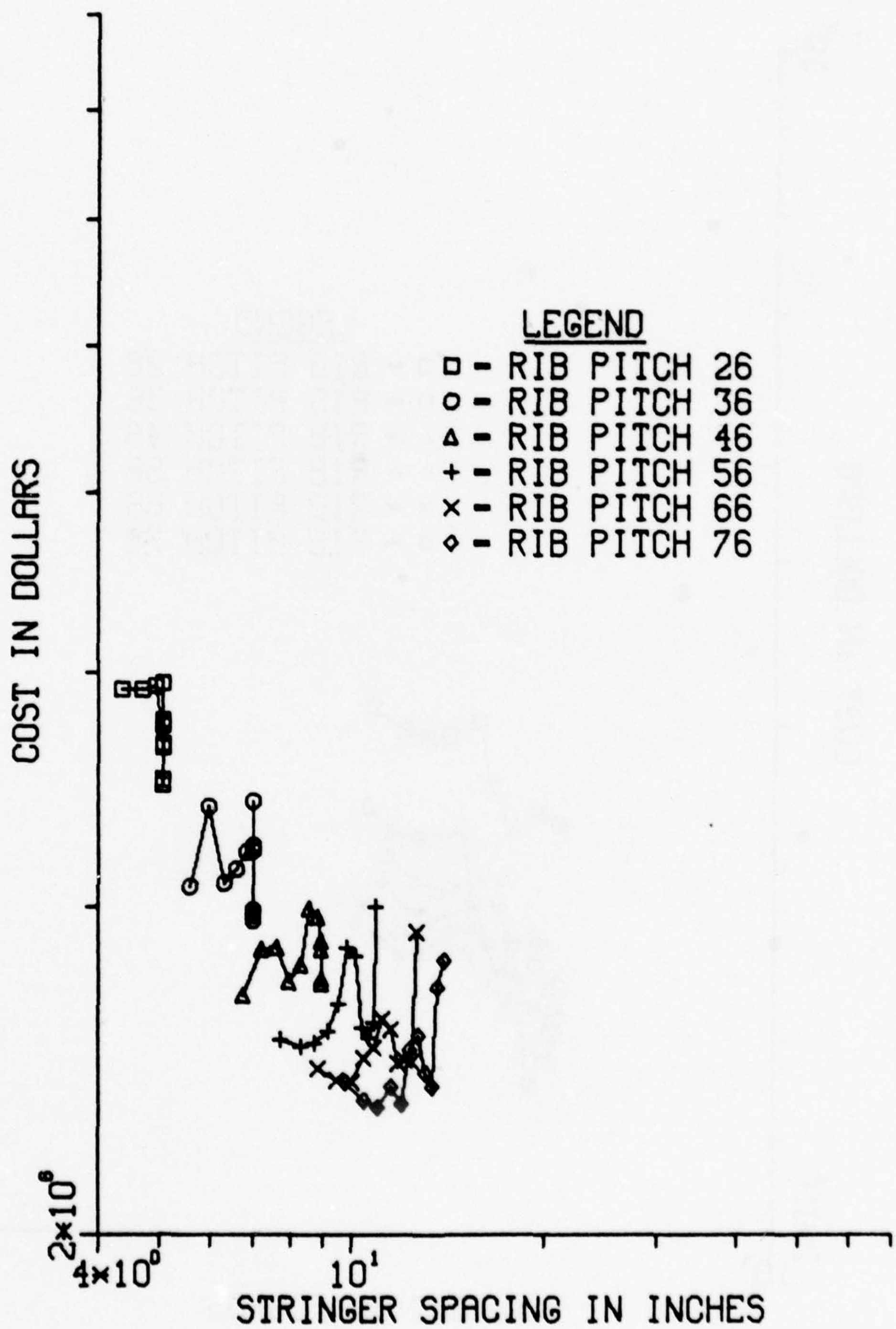

INT TEE
LEGEND
□ - RIB PITCH 26
○ - RIB PITCH 36
△ - RIB PITCH 46
+ - RIB PITCH 56
× - RIB PITCH 66
◇ - RIB PITCH 76
COST IN DOLLARS
2×10^6
4×10^0
10^1
STRINGER SPACING IN INCHES

INT ZEE



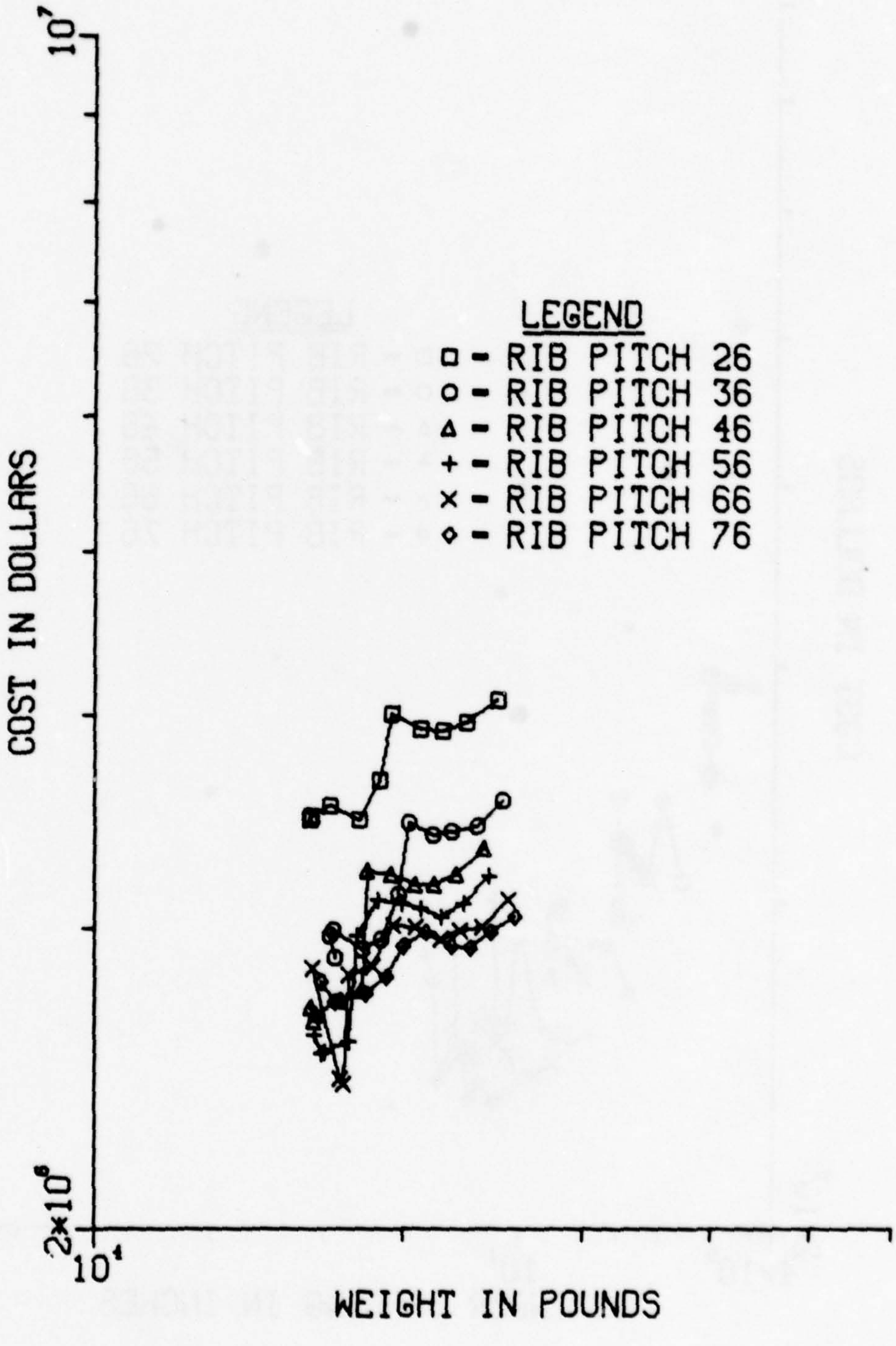
LEGEND
□ - RIB PITCH 26
○ - RIB PITCH 36
△ - RIB PITCH 46
+ - RIB PITCH 56
× - RIB PITCH 66
◇ - RIB PITCH 76
COST IN DOLLARS
2×10⁶
4×10⁰
10¹
STRINGER SPACING IN INCHES

SEP JAY



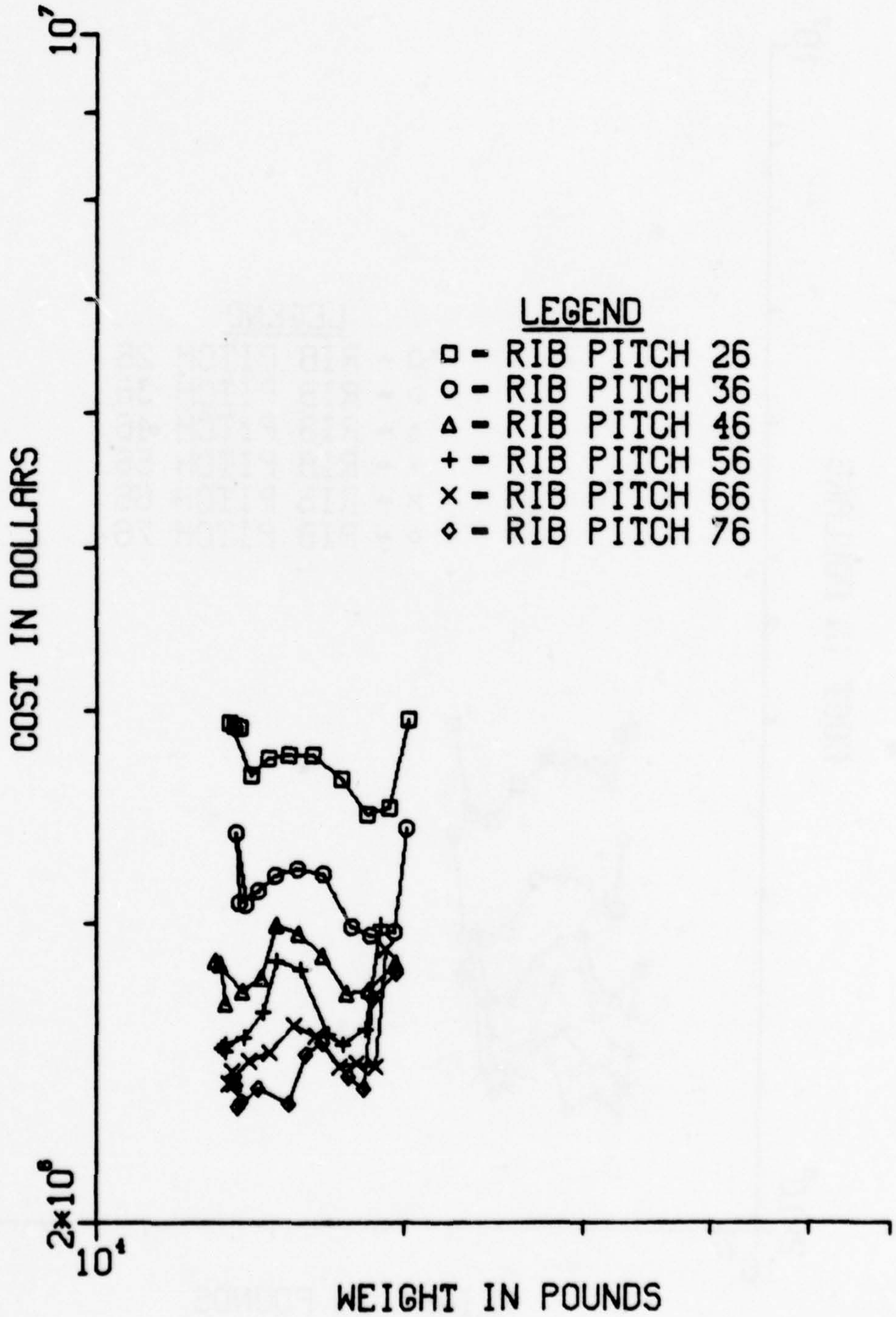
LEGEND
□ - RIB PITCH 26
○ - RIB PITCH 36
△ - RIB PITCH 46
+ - RIB PITCH 56
× - RIB PITCH 66
◇ - RIB PITCH 76
COST IN DOLLARS
2×10⁶
4×10⁰
10¹
STRINGER SPACING IN INCHES

INT BLADE



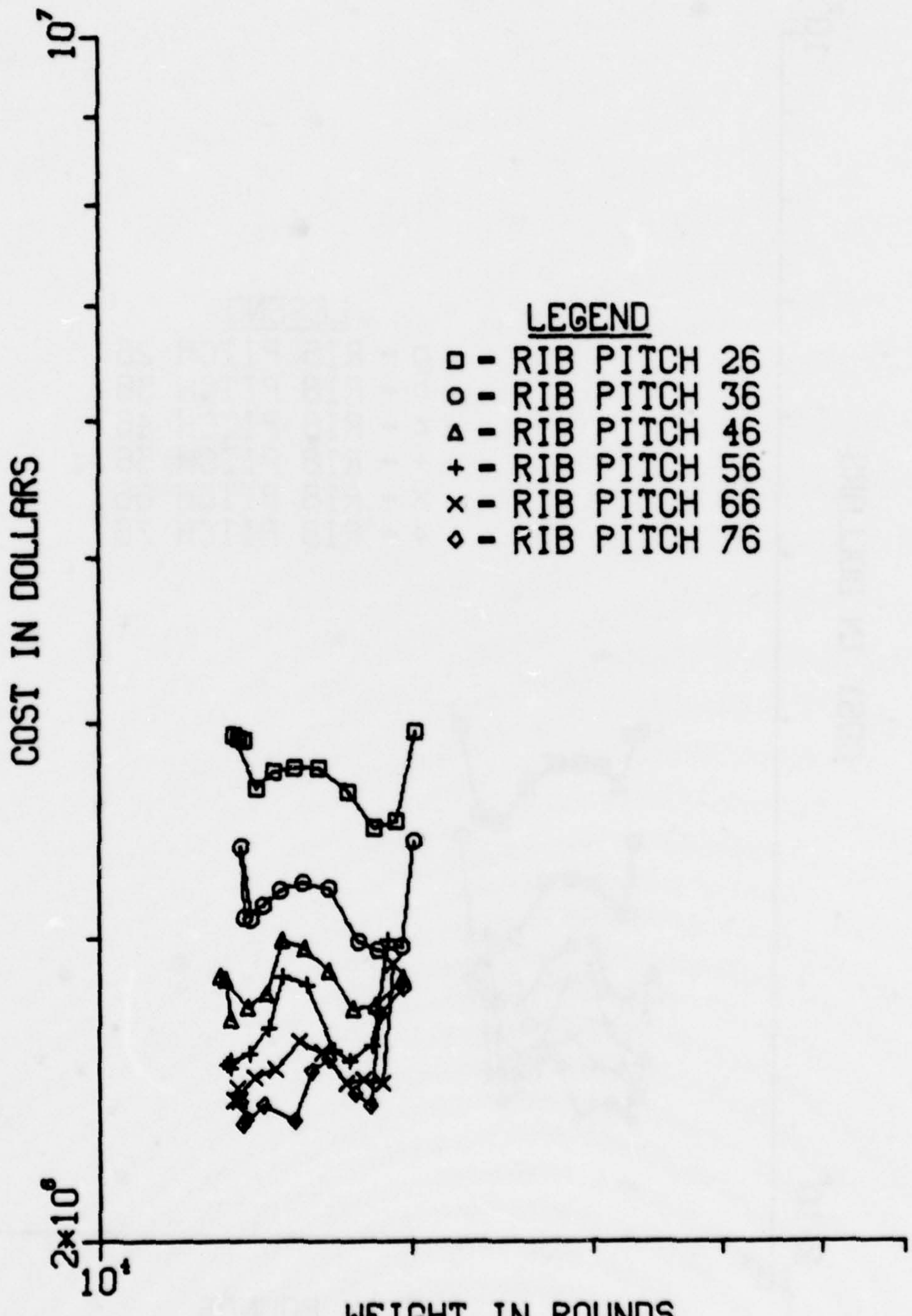
10^7
COST IN DOLLARS
2×10^6
10^4
WEIGHT IN POUNDS
LEGEND
□ - RIB PITCH 26
○ - RIB PITCH 36
△ - RIB PITCH 46
+ - RIB PITCH 56
× - RIB PITCH 66
◇ - RIB PITCH 76

INT TEE



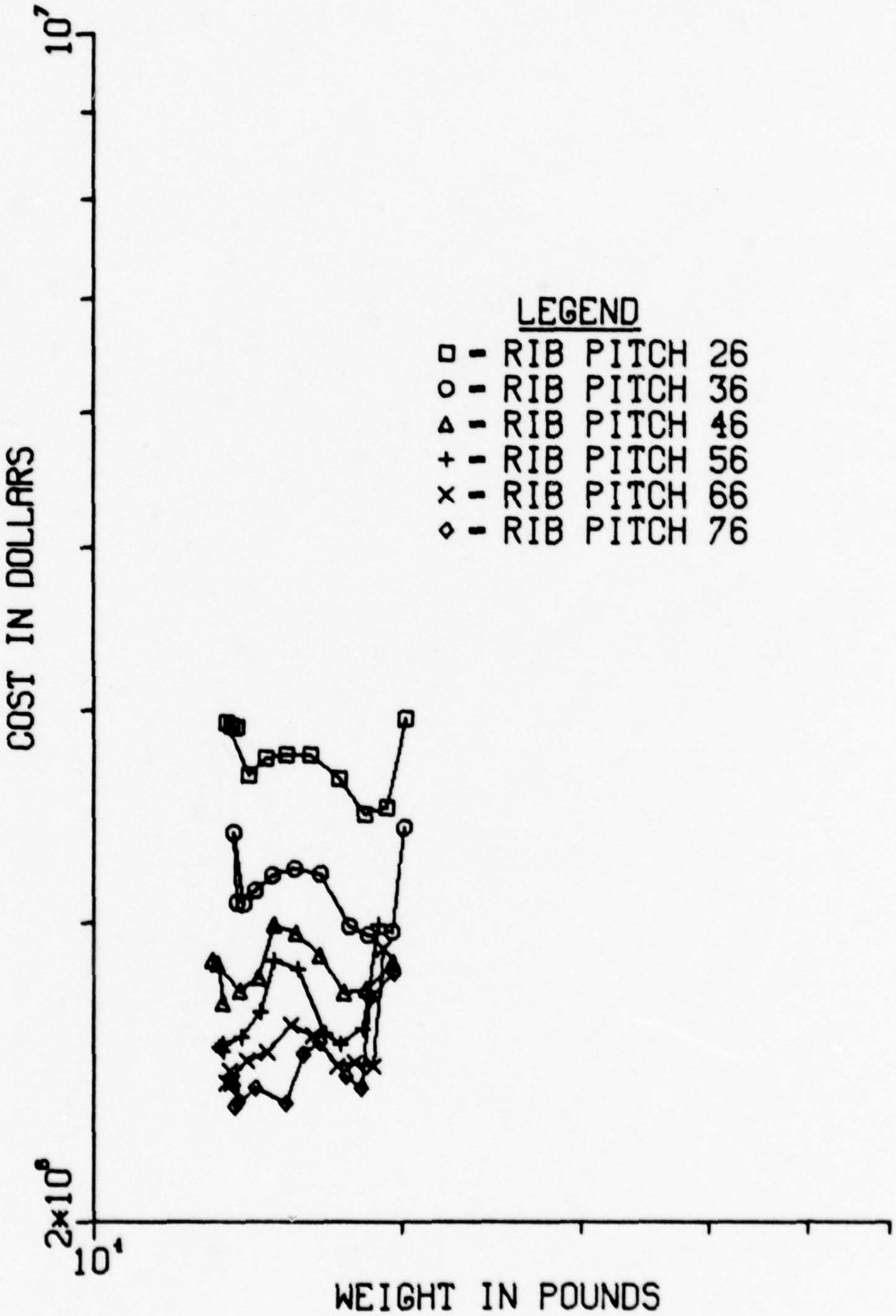
10^7
COST IN DOLLARS
LEGEND
□ – RIB PITCH 26
○ – RIB PITCH 36
△ – RIB PITCH 46
+ – RIB PITCH 56
× – RIB PITCH 66
◇ – RIB PITCH 76
2×10^6
10^4
WEIGHT IN POUNDS

INT ZEE



10^7
COST IN DOLLARS
LEGEND
□ - RIB PITCH 26
○ - RIB PITCH 36
△ - RIB PITCH 46
+ - RIB PITCH 56
× - RIB PITCH 66
◇ - RIB PITCH 76
2×10^6
10^4
WEIGHT IN POUNDS

SEP JAY



10^7
COST IN DOLLARS
$2*10^6$
10^4
WEIGHT IN POUNDS
LEGEND
□ - RIB PITCH 26
○ - RIB PITCH 36
△ - RIB PITCH 46
+ - RIB PITCH 56
× - RIB PITCH 66
◇ - RIB PITCH 76

APPENDIX G

RIB DATA

This is a reproduction of the VDEP printout which gave the rib data for a wing surface with material type--Aluminum 2024-T6, surface load of 250,000 pounds, integral zee stringer type, and rib pitch of 26 inches.

RIB DATA

RIB NO	RIB STA	FULL CHORD	BOX CHORD	AVG. H
1	0.00	420.93	214.67	58.27
2	26.00	413.76	211.02	57.07
3	52.01	406.60	207.36	55.87
4	78.01	399.43	203.71	54.68
5	104.02	392.26	200.05	53.48
6	130.02	385.10	196.40	52.29
7	156.03	377.93	192.75	51.09
8	182.03	370.77	189.09	49.89
9	208.03	363.60	185.44	48.70
10	234.04	356.43	181.78	47.50
11	260.04	349.27	178.13	46.31
12	286.05	342.10	174.47	45.11
13	312.05	334.93	170.82	43.91
14	338.06	327.77	167.16	42.72
15	364.06	320.60	163.51	41.52
16	390.06	313.43	159.85	40.33
17	416.07	306.27	156.20	39.13
18	442.07	299.10	152.54	37.93
19	468.08	291.93	148.89	36.74
20	494.08	284.77	145.23	35.54
21	520.09	277.60	141.58	34.35
22	546.09	270.43	137.92	33.15
23	572.09	263.27	134.27	31.96
24	598.10	256.10	130.61	30.76
25	624.10	248.94	126.96	29.56
26	650.11	241.77	123.30	28.37
27	676.11	234.60	119.65	27.17
28	702.12	227.44	115.99	25.98
29	728.12	220.27	112.34	24.78
30	754.12	213.10	108.68	23.58
31	780.13	205.94	105.03	22.39
32	806.13	198.77	101.37	21.19
33	832.14	191.60	97.72	20.00
34	858.14	184.44	94.06	18.80
35	884.15	177.27	90.41	17.60
36	910.15	170.10	86.75	16.41
37	936.16	162.94	83.10	15.21
38	962.16	155.77	79.44	14.02
39	988.16	148.61	75.79	12.82
40	1014.17	141.44	72.13	11.62
41	1040.17	134.27	68.48	10.43
42	1069.18	126.28	64.40	9.09

APPENDIX H

SKIN STRINGER CONSTRUCTION

This appendix is a reproduction of the VDEP print-out of the skin stringer construction for a wing designed with material type of Aluminum 2024-T6, surface load of 250,000 pounds, integral zee stringer type, and rib pitch of 26 inches.

SKIN STRINGER CONSTRUCTION
INTEGRAL ZEE STRINGER
COMPRESSION COVER

RIB NO	STA (IN)	TBAR (IN)	BS (IN)	TS (IN)	BW (IN)	TW (IN)
1	0.0	.234	5.26	.131	1.75	.113
2	26.0	.192	4.77	.108	1.59	.092
3	52.0	.144	3.79	.081	1.26	.069
4	78.0	.144	1.71	.081	.57	.069
5	104.0	.162	4.38	.091	1.46	.078
6	130.0	.169	4.46	.094	1.49	.081
7	156.0	.167	4.44	.093	1.48	.080
8	182.0	.164	4.40	.092	1.47	.079
9	208.0	.162	4.37	.090	1.46	.078
10	234.0	.159	4.34	.089	1.45	.076
11	260.0	.157	4.31	.088	1.44	.075
12	286.0	.155	4.27	.087	1.42	.074
13	312.1	.152	4.23	.085	1.41	.073
14	338.1	.149	4.20	.084	1.40	.072
15	364.1	.147	4.16	.082	1.39	.070
16	390.1	.144	4.13	.081	1.38	.069
17	416.1	.144	4.03	.081	1.34	.069
18	442.1	.144	3.95	.081	1.32	.069
19	468.1	.144	3.88	.081	1.29	.069
20	494.1	.144	3.79	.081	1.26	.069
21	520.1	.144	3.69	.081	1.23	.069
22	546.1	.144	3.60	.081	1.20	.069
23	572.1	.144	3.52	.081	1.17	.069
24	598.1	.144	3.42	.081	1.14	.069
25	624.1	.144	3.30	.081	1.10	.069
26	650.1	.144	3.18	.081	1.06	.069
27	676.1	.144	3.10	.081	1.03	.069
28	702.1	.144	2.99	.081	1.00	.069
29	728.1	.144	2.85	.081	.95	.069
30	754.1	.144	2.70	.081	.90	.069
31	780.1	.144	2.60	.081	.87	.069
32	806.1	.144	2.47	.081	.82	.069
33	832.1	.144	2.30	.081	.77	.069
34	858.1	.144	2.09	.081	.70	.069
35	884.1	.144	1.98	.081	.66	.069
36	910.2	.144	1.83	.081	.61	.069
37	936.2	.144	1.62	.081	.54	.069
38	962.2	.144	1.28	.081	.43	.069
39	988.2	.144	1.19	.081	.40	.069
40	1014.2	.144	1.05	.081	.35	.069
41	1040.2	.144	.83	.081	.28	.069
42	1069.2	.144	0.00	.081	0.00	.069

Skin Weight = 1616.9 lb
Stgr Weight = 1000.3 lb 61 stgrs
Cover Weight = 2617.2

APPENDIX I

STRINGERS PER RIB NUMBER

This appendix is a table of selected calculations of the stringers per rib number in the wing designed by VDEP.

STRINGERS PER RIB NUMBER (EXAMPLES)

Compression Cover		Tension Cover	
Rib #	Stringers at Rib #	Rib #	Stringers at Rib #
1.	40.81	1.	31.80
2.	44.23	2.	36.76
3.	54.71	3.	52.49
4.	119.12	4.	114.44
5.	45.07	5.	41.33
6.	44.03	6.	39.91
7.	43.41	7.	39.17
8.	42.91	8.	38.59
9.	42.43	9.	38.47
10.	41.88	10.	38.26
12.	40.85	12.	37.84
14.	39.80	14.	37.56
16.	38.70	16.	37.17
18.	38.60	18.	37.02
20.	38.31	20.	36.76
21.	38.36	21.	36.77
22.	38.31	22.	36.77
23.	38.14	23.	36.68
24.	38.19	24.	36.68
25.	38.47	25.	36.90
26.	38.77	26.	37.13
28.	38.79	28.	37.29
30.	40.25	30.	38.67
32.	41.04	32.	39.29
34.	45.00	34.	43.14
36.	47.40	36.	45.41
38.	62.06	38.	59.73
40.	68.69	40.	65.57
41.	82.50	41.	79.62

APPENDIX J

VDEP DEVELOPMENT

VEHICLE DESIGN AND EVALUATION PROGRAM (VDEP) DEVELOPMENT

NAS 2-5718	NAS 1-11343
<u>Sizing</u> Weight Geometry Performance (Prelim)	<u>Sizing</u> + Balance + C. G. Range + Area Distribution + Plotting + Graphics
<u>External Loads</u>	<u>External Loads</u>
<u>Structural Synthesis</u> BOXSIZ (Wing Box) 1870 (Fuselage Shell)	<u>Structural Synthesis</u> - 1870 (Fuselage Shell) + APAS (Fuselage Shell) + Graphics
<u>Part Definition</u> Box Structure Fuselage Shell	<u>Part Definition</u> + Leading Edge + Trailing Edge + Tips + Fuselage Penalty
<u>Cost</u> Manufacturing Standard Hours Realization Material	<u>Cost</u> + Tooling + Engineering + First Unit + Program + Direct Operating + Return on Investment + Graphics

VEHICLE DESIGN AND EVALUATION PROGRAM
(VDEP) DEVELOPMENT (Continued)

NAS 1-12506	NAS 1-13285
Sizing	Sizing + Aerodynamics + Missions + Performance + Multibodies + Hydrogen Fuel + Methane Fuel + Mass Distribution & Inertia
External Loads	External Loads + Aerodynamic Loads + Landing Gear Loads + Pressure Loads + Net Loads
Structural Synthesis - BOXSIZ (Wing Box) + APAS (Wing Box) + Fatigue Criteria + Fracture Criteria	Structural Synthesis
Part Definition	Part Definition
Cost	Cost + Manufacturing CER Model

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